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The 1979  
Goddard Space Flight Center  
Battery Workshop

G. Halpert, *Editor*

A Workshop held at  
Goddard Space Flight Center  
Greenbelt, Maryland  
November 13 - 15, 1979

**NASA**



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National Aeronautics  
and Space Administration

**Scientific and Technical  
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## PREFACE

This, the 12th Annual Battery Workshop was attended by manufacturers, users, and government representatives interested in the latest results of testing, analysis, and development of the sealed nickel cadmium cell system. Also included were sessions on metal hydrogen and lithium cell technology and applications. The purpose of the Workshop was to share flight and test experience, stimulate discussion on problem areas, and to review the latest technology improvements.

The papers presented in this document have been derived from transcripts taken at the Workshop held at the Goddard Space Flight Center on November 13 to 15, 1979. The transcripts were lightly edited with the speaker's vugraphs assembled at the end of each presentation for uniformity.



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## INTRODUCTION

G. Halpert  
Goddard Space Flight Center

Welcome to Goddard Space Flight Center and the 1979 NASA/GSFC Battery Workshop. We have planned an interesting electrochemical cell and battery technology program.

To begin, R. Riebling from NASA Headquarters will describe the present NASA electrochemical research and development effort. Secondly, L. Slifer from GSFC will summarize the results of the OSTA Power Subsystems Committee which met in August. The third event will be a panel discussion on a subject of much concern, "Bridging the Gap between Technology and Flight Hardware." Panel dialogues have been successful in past workshops, and this year's panel should continue the trend. The lithium cell application and safety session follows.

Wednesday morning the subjects will be cell and battery technology and test and flight experience. The accelerated test analyses continue, and their results will be the subject of an expanded session on Thursday, as well as continuing discussions on nickel hydrogen cell and battery design and test results.

We at NASA/GSFC again welcome you and hope that through your active participation you will find this year's workshop to be beneficial.

For your information, we have included a list of the acquisition numbers for all workshop proceedings dating back to 1970.

### BATTERY WORKSHOP PROCEEDINGS

		Doc. No.
1978	Workshop	79N28669
1977	Workshop	79N21565
1976	Workshop	77N21550
1975	Workshop	76N24704
1974	Workshop	75N16976
1973	Workshop (1st Day)	75N15152
	Workshop (2nd Day)	75N17808

		Doc. No.
1972	Workshop (1st Day)	73N21956
	Workshop (2nd Day)	73N21957
1971	Workshop (Vol. 1)	72N27061
	Workshop (Vol. 2)	72N27062
1970	Workshop (1st Day)	71N28659
	Workshop (2nd Day)	71N28672

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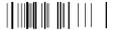
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SESSION I

TECHNOLOGY DEVELOPING FLIGHT HARDWARE

F. Ford, Chairman  
Goddard Space Flight Center



## OVERVIEW OF NASA BATTERY TECHNOLOGY PROGRAM

R. Riebling  
NASA Headquarters

I am going to be highlighting OAST's technology program in batteries for space applications. I will be presenting highlights only, not only because of the time constraints, but also because many subsequent speakers will be presenting details of the program elements, and because there will be an article in the special January issue of the "Advanced Battery Technology Newsletter," which will discuss the mass of OAST battery technology programs in greater detail.

The electrochemistry program in OAST includes not only batteries but also fuel cells and electrolysis technology. Because this is a battery workshop, I am going to be restricting my remarks today only to the battery portion of the program.

And finally, I will be discussing only the technology work that we are sponsoring. The flight experience will be discussed on Wednesday.

The OAST battery technology program is funded at roughly \$2 million a year, and in FY 80 that level of funding will be continued. Of that amount, approximately two-thirds is managed and spent by the Lewis Research Center in Cleveland; and one-third, by the Jet Propulsion Laboratory in Pasadena, California. Of that same total of \$2 million, approximately one-half is in-house work, and the remaining half is contracting with industry and is awarded as grants to universities.

(Figure 1-1)

This vugraph indicates some of the program elements or what is in the program. First, we have advanced ambient temperature alkaline secondaries, which are primarily nickel-cadmium cells in batteries.

Then, we have secondaries with multi-kilowatt-hour storage capacity primarily for lower orbital applications that we see in the future. Those are mainly toroidal nickel cadmium, and there is a fuel cell electrolizer program going on at the Johnson Space Center. But, since that is not a battery program, it will not be discussed today.

The program also includes ambient temperature lithium batteries, both primary and secondary, high-energy density, higher than ambient temperature secondaries. Finally, metal-gas secondaries, primarily silver hydrogen, and high-capacity nickel hydrogen are included in the program.

(Figure 1-2)

The general objectives of all these elements of the technology program are to increase the useful energy density; to increase the storage capacity, primarily for lower orbital applications; to

extend the useful life; to extend the cycle capability for secondaries, of course; and to always improve the reliability and the safety of these devices.

(Figure 1-3)

This chart summarizes some of our near-term specific objectives. In the interests of time, I am not going to cover every cell in this matrix, but this chart will be in the proceedings.

By the near term we mean the mid-1980s for the most part. By 1983 to 1985, we would hope to have brought the technology along to the state where electrochemical systems would have these particular characteristics for our applications.

The first column on this chart indicates what those applications are. As you can see, it spans the spectrum of all the regions of space in which we are interested from low-Earth orbit all the way out to geosynchronous planetary orbiters, landers, and probes. Each of those has its own special requirements in terms of capacity and energy density.

The second column indicates the major electrochemical system which is being advanced for those applications. You can see that we have some nickel-cadmium work going on, as well as some silver hydrogen sodium chalcogenide and several lithium systems.

Among these specific objectives, with the exception of the low-Earth orbiters where our major objective is the 100-ampere hour capacity, the primary near-term objective for all of the other application systems are the cell energy density and the battery life. The numbers in those columns represent our near-term objectives.

For completion, we have indicated cycle life and corresponding depth of discharge to add some meaning to those numbers.

(Figure 1-4)

In the remainder of my presentation, I want to cover just some of the highlights of these different program elements. In advanced alkaline secondaries, two primary objectives are to develop a fundamental understanding of nickel cadmium, cell degradation, and failure mechanisms and to embody these in some kind of a useful, reliable, predictive model that users can actually employ.

Also, we would like to achieve longer life, i.e., greater than 900 or 1000 cycles, greater than 10 years, and get the specific energy up greater than 26 watt-hours per kilogram with the nickel-cadmium system.

An approach to this is improvements in separator technology, technology of electrodes, and reconditioning procedures. Most of that you will hear about subsequently.

There has been a good deal of progress going on in this entire program, but in limited time, it is very difficult to convey all of that progress. Fortunately, a number of the speakers who will follow me over the next several days will be highlighting their progress in a lot more detail.

Recent progress in nickel cadmium, however, includes the attainment of superior hydrogen recombination rates under reversal conditions. It has been demonstrated by Lewis, PRW, in C/2 discharge rates and some new experimental cell design, which I understand will be discussed on Wednesday.

Also, a failure model for nickel-cadmium cells has been developed and partially validated at JPL, and that will be discussed on Thursday.

(Figure 1-5)

The objective of multi-kilowatt-hour storage technology is to establish the feasibility of a greater than 100-ampere hour, greater than 5-year life, and relatively low-cost nickel-cadmium cell of a toroidal configuration relatively soon, by the end of this fiscal year. Then, depending on how feasible it looks, further development may be undertaken.

Also, NASA/OAST is interested in a preliminary evaluation of nickel-hydrogen batteries somewhere in the range of 65 watt-hours per kilogram for high capacity, lower orbit applications. While most of that work is being conducted by the Air Force for tracking, there is a small in-house program going on at Lewis to take a closer look at that technology for our applications.

Recent progress in this area includes the design of a toroidal cell and investigation of fabrication, and sealing techniques have been initiated by Lewis.

(Figure 1-6)

Lithium systems—Work is going on both in primaries and secondaries. One objective is to demonstrate a safe 300 or more watt-hour per kilogram primary battery for probe applications with a 5-year storage life at relatively high drain conditions by the end of FY 84.

Another objective is to demonstrate a 220-watt-hour per kilogram secondary battery for lander applications by the end of FY 82. It may turn out that a target of 150 watt-hours per kilogram might be more reasonable. That is under consideration.

The approach in the lithium program is, first of all, to gain a fundamental understanding of the physical and chemical processes which are unique to lithium-based systems; also, to develop and characterize new or improved electrodes, electrolytes, and materials; and third, to develop a NASA in-house capability to fabricate prototype cells and to write design specifications.

In the past, NASA's lithium technology program has been, in my estimation, overly beholden to contractors and their capabilities. We now feel NASA would benefit from having a stronger in-house capability in lithium systems. Consequently, the lithium program has been reoriented along those lines within the past 6 months.

Recently, lithium anode conducting film modeling has been going on at JPL. Lithium hexafluoroarsenate has been selected as a primary candidate electrolyte for study in secondary cells. These will be discussed in more detail by several speakers this afternoon.

(Figure 1-7)

In the high energy density secondary systems, we have an objective of establishing the feasibility of 5-year again graded in 200 watt-hour per kilogram energy density secondary batteries by the end of FY 82. This work is being carried out at the Lewis Research Center. The approach centers about the use of liquid sodium anodes, thin beta alumina solid electrolytes, and solid transition metal, chalcogenides for reversible intercalation of sodium ions.

Recent progress has been a demonstration of the feasibility irreversibly intercalating up to two equivalents of sodium ion in vanadium disulfide and  $\text{NiPS}_3$  at high temperatures.

(Figure 1-8)

Finally, in the metal gas secondaries, we want to complete both our preliminary evaluation of a 77-watt-hour per kilogram 50-ampere hour silver hydrogen cell this fiscal year and that evaluation of nickel-hydrogen batteries which I discussed earlier. This subject overlaps that of the multi-kilowatt-hour energy storage program element.

Recent progress at the Lewis Research Center includes demonstration of a 50-ampere hour 80-watt-hour per kilogram silver hydrogen cell which has completed 600 cycles. Also, in more basic research at that center, certain silver electrodes have demonstrated 1500 cycles in single cell tests.

Before concluding, I should point out that NASA is also advancing the technology of secondary nickel-zinc systems for terrestrial applications under its technology utilization program. This is work which is not directly sponsored by OAST. NASA is also responsible for several electrochemical technology programs or projects which are being carried out for the Department of Energy.

These generally center about batteries for electric and hybrid vehicles and energy storage for utility power generation. But our emphasis, or at least the emphasis in my presentation, has been on space technology, so I won't discuss those any further here.

## DISCUSSION

LEAR: I would like to ask you about the silver hydrogen tests that were conducted at NASA Lewis. What sort of criteria were you testing with the silver hydrogen cells?

RIEBLING: I regret I cannot give you very many details of that, but there is a representative from Lewis in the audience. I would like him to identify himself and hopefully respond to that question.

SMITHRICK: The question that was asked on the silver hydrogen cycle life data, as I remember it, was what were the specific test conditions for the cycle life?

Well, it was an accelerated synchronous orbit test, an 8-hour cycle, consisting of 6.8 hours of charge and 1.2 hours of discharge. The discharge and charge were both at constant currents, and

the depth of discharge was 75 percent. If the voltage should drop below 0.9 volt, that is defined as the end of life.

The data presented was for a 50-ampere hour cell. There is also some data for a 35-ampere hour cell. The 35-ampere hour cell was cycled for over 960 cycles, and the test is still being continued.

LEAR: What was the constant current rate that you had during the charge and the discharge?

SMITHRICK: The cell that was presented was a 50-ampere hour cell. So, the current is 50-ampere hours divided by 1.2 hours, whatever that number comes out to. You know for a 75-percent depth of discharge, I don't have a calculator with me, but that is the way we figure it out. Of course, the same thing would be for the charge.

You take 50-ampere hours and multiply it by 0.75 and that comes out to—well, whatever it comes out to, and just divide that.

RIEBLING: I should say that the silver hydrogen work is not a large or major element of our technology program. This work is nearly complete and is being phased out. The primary reason is that the metal gas cells are being developed by other agencies, and probably the nickel-hydrogen systems are the ones that will likely find themselves in use in the near term, so the silver hydrogen is being relinquished to the back burner for a while.

PROGRAM ELEMENTS

- ADVANCED AMBIENT-TEMPERATURE ALKALINE SECONDARIES
- MULTI-KWH CAPACITY SECONDARIES
- AMBIENT-TEMPERATURE LITHIUM PRIMARIES AND SECONDARIES
- HIGH-ENERGY-DENSITY, ABOVE AMBIENT TEMPERATURE SECONDARIES
- METAL-GAS SECONDARIES

Figure 1-1

GENERAL OBJECTIVES

ADVANCE PRIMARY AND SECONDARY SPACE BATTERY TECHNOLOGY TO INCREASE:

- ENERGY DENSITY
- STORAGE CAPACITY (LEO)
- USEFUL LIFE
- CYCLE CAPABILITY (SECONDARIES)
- RELIABILITY AND SAFETY

Figure 1-2

NEAR-TERM SPECIFIC OBJECTIVES

PRIMARY APPLICATION	ELECTROCHEMICAL SYSTEM	CAPACITY AH	CELL ENERGY DENSITY, WH/KG	BATTERY LIFE, YR	CYCLE LIFE	DOD %
LOW EARTH ORBITERS	Ni-Cd (TORROIDAL)	100	30	5	25,000	20
GEOSYNCHRONOUS ORBITERS	Ag-H <sub>2</sub>	50	66	10	1,000	75
	Na/CHALCOGENIDE	100	300	5-10	1,000	75
PLANETARY ORBITERS	Li-TiS <sub>2</sub>	5-10	220	10	500	65
PLANETARY LANDERS	Li-TiS <sub>2</sub>	5-10	220	10	5,000	35
PLANETARY PROBES	LiSOCL <sub>2</sub>	20-50	330	5	PRIMARY	80

Figure 1-3

ADVANCED ALKALINE SECONDARIES

POTENTIAL APPLICATIONS

- GEOSYNCHRONOUS ORBITERS
- NEAR-TERM PLANETARY ORBITERS

OBJECTIVES

- DEVELOP FUNDAMENTAL UNDERSTANDING OF NiCd CELL DEGRADATION AND FAILURE MECHANISMS, EMBODY IN PREDICTIVE MODEL
- ACHIEVE LONG LIFE (>900 CYCLES, >10 YR) AND HIGH SPECIFIC ENERGY (>26 WHR/KG) WITH NiCd BATTERIES THROUGH IMPROVEMENTS IN SEPARATORS, ELECTRODES, AND RECONDITIONING PROCEDURES

RECENT PROGRESS

- SUPERIOR H<sub>2</sub> RECOMBINATION AT  $\leq 0V$ , DEMONSTRATED BY LeRC/TRW AT C/2 OVERDISCHARGE RATES IN NEW EXPERIMENTAL CELL DESIGNS
- FAILURE MODEL FOR NiCd CELLS DEVELOPED AND PARTIALLY VALIDATED AT JPL

Figure 1-4

POTENTIAL APPLICATIONS

- LOW-EARTH ORBITERS

OBJECTIVES

- DETERMINE FEASIBILITY OF  $>100$  A-HR,  $>5$ -YR LIFE,  $<\$30$ /W-HR TORROIDAL  $\text{NiCd}$  CELL BY EOFY'80
- COMPLETE PRELIMINARY EVALUATION OF  $\text{Ni-H}_2$  BATTERIES FOR HIGH-CAPACITY LOW-EARTH ORBIT APPLICATIONS IN FY'80

RECENT PROGRESS

- DESIGN OF TORROIDAL CELL, INVESTIGATION OF FABRICATION AND SEALING TECHNIQUES INITIATED BY LeRC

Figure 1-5

POTENTIAL APPLICATIONS

- PRIMARY - PLANETARY PROBES
- SECONDARY - PLANETARY ORBITERS, LANDERS

OBJECTIVES

- DEMONSTRATE SAFE 300 WHR/KG PRIMARY PROBE BATTERIES WITH 5-YR STORAGE LIFE AT C/1 BY END OF FY'84
- DEMONSTRATE 220 WHR/KG SECONDARY LANDER BATTERIES BY END OF FY'82

RECENT PROGRESS (PROGRAM REORIENTED LAST QTR OF FY'79)

- LITHIUM ANODE CONDUCTING FILM MODELING INITIATED AT JPL
- $\text{LiAsF}_6$  SELECTED AS CANDIDATE ELECTROLYTE FOR STUDY IN SECONDARY CELLS

Figure 1-6

POTENTIAL APPLICATIONS

- GEOSYNCHRONOUS, PLANETARY ORBITERS

OBJECTIVE

- ESTABLISH FEASIBILITY OF 5-YR,  $>200$  WH/KG SECONDARY BATTERY BY EOFY'82

RECENT PROGRESS

- FEASIBILITY OF REVERSIBLY INTERCALATING UP TO 2 EQUIVALENTS OF  $\text{Na}^+$  IN  $\text{VS}_2$  AND  $\text{NiPS}_3$  AT  $130^\circ\text{C}$ . DEMONSTRATED BY LeRC/EIC.

Figure 1-7

POTENTIAL APPLICATIONS

- GEOSYNCHRONOUS, LOW-EARTH ORBITERS

OBJECTIVES

- COMPLETE PRELIMINARY EVALUATION OF 77 WH/KG, 50 AH  $\text{Ag-H}_2$  CELLS IN FY'80
- COMPLETE PRELIMINARY EVALUATION OF  $\text{Ni-H}_2$  BATTERIES FOR HIGH-CAPACITY LOW-EARTH ORBIT APPLICATIONS IN FY'80

RECENT PROGRESS

- 50 AH, 80 WH/KG  $\text{Ag-H}_2$  CELL HAS COMPLETED 600 CYCLES AT LeRC

Figure 1-8



RECOMMENDATIONS OF OSTA FLIGHT TECHNOLOGY  
IMPROVEMENT WORKSHOP - POWER SUBSYSTEMS PANEL

L. Slifer  
NASA/GSFC

(Figure 1-9)

This presentation discusses the recommendations of the Power Subsystems Panel of the Office of Space and Terrestrial Application Workshop, which was held in July and August 1979. The primary thrust of the workshop was directed at radiometric problems which have been showing up. But, in the process, several panels were developed to contribute to this workshop.

(Figure 1-10)

The Radiometric Instruments and Calibrations Panel, as I said, was the primary one. There was also concern for electromechanical subsystems, attitude control and determination, and power systems in that each of these subsystems affects what happens with the experiments and instruments on board a spacecraft. If these systems are not working properly, the experiments and instruments are not working right.

(Figure 1-11)

This report is essentially the report from the power panel, which, as you can see, consisted of a large variety of power systems people from the various users, both government and industry.

(Figure 1-12)

The objective of the workshop was to identify the technology needs that become apparent through previous problems. I might say that throughout the workshop, there was a lot of difficulty with how to talk about problems versus failures versus anomalies, and so forth, because of sensitivities of people there. It was related to past and ongoing missions. In other words, problems that have not been completely solved in the past, new problems that we are facing right now, and near-future potentials; not problems that are going to come up because we are going to have space platforms or highly advanced technology requirements coming up in the more distant future.

In the process, though, we could not ignore the direction that things are going. Since we were looking at past problems and the direction they are leading, obviously the future could not be totally excluded.

We did consider both the spacecraft power subsystem and power supplies for the experiments and instruments. The real bottom-line objective was to come up with recommendations for technology development, essentially define areas that needed development. We did not come up with a

specific program. I should emphasize that these conclusions and recommendations come from the power panel, not from NASA, not from Goddard, not from me, but from the panel as a group working together.

(Figure 1-13)

The approach used was to identify technology problems. Just about everyone on the panel made a presentation based on problems that had been seen at his agency or with regard to particular spacecraft that he has worked on, or was associated with.

We also looked at papers from the other panels to see where there were relationships between power system problems and other panel problems. Initially, we categorized them by areas.

(Figure 1-14)

Essentially, the basic areas are the power subsystem, the system, the array, the batteries, and so forth. Then, these problems were translated into technology development requirements.

(Figure 1-15)

We classified the requirements into a second group of work categories, and then we did some prioritizing.

(Figure 1-16)

This is the set of work categories, listed in priority order, indicating the areas that are problem areas. The ones noted with an asterisk are those which relate, in one way or another, to batteries themselves.

(Figure 1-17)

We did note particularly two other problem areas. In the one area, the lightweight structures of the arrays cause problems with spacecraft orientation and control systems. In the other area, thermal control can be very serious as far as battery performance is concerned. It is a very important area, but it is not something that battery people can do much about. It is up to thermal control systems to give us good thermal control.

(Figure 1-18)

Now, we get into the specific categories in a little more detail. Although it is currently primarily a problem with solar arrays, there are requirements for analytical modeling in batteries. It is not only a matter of the DC modeling, but we are getting into the area where AC problems require solution. We need to know the AC analytical model for batteries.

There is very little data that exists, and it is a very difficult field to work in right now. The payoff on work in this area is that we safeguard against bus instability. We have run into that in flight spacecraft and can avoid harmful interactions between the array and filter components. By defining the source impedance at the load bus, we could model the spacecraft power system better. We really need this model because the whole systems are getting so large that all-up system tests cannot be performed anymore.

(Figure 1-19)

A second area is the state of health monitoring. The conclusions of the power panel indicate the need for a better state of health monitoring, more detailed monitoring of what is happening in the power system in flight.

There are a couple of reasons for this: One is that we are getting away from the point where we are in constant contact with the spacecraft. In order to have the spacecraft power system functioning properly, we need more monitoring of what is going on, and, in fact, onboard processing of what is going on in order to handle the power subsystem when we cannot handle it from the ground. Extensive ground monitoring has been required in the past, and a lot of ground analytical work has been required, to the extent of actually flying the spacecraft by wire, you might say, continually controlling it from the ground in order to keep things working. On some recent spacecraft this has been particularly a result of unanticipated poor performance of the battery compared to the desired performance.

(Figure 1-20)

I will not go into much new component development for high voltage and high-power components. The only thing that does relate to the battery is that the power subsystems on the larger spacecraft are getting up to the point where tremendous currents are required. Unless the bus voltages go up, the currents result in tremendous weight penalties.

With the increasing bus voltages, it means either circuitry to take care of it, boost circuitry, or more cells in series in the battery. That, in turn, says something about reliability; also, in turn, says something about the problem of flying multiple batteries to back each other up.

(Figure 1-21)

The high voltage technology was really a matter of reliable-type technology related to spacecraft experiments.

(Figure 1-22)

Array cell testing is related to the solar array, its cells, and the testing in order to get reliability from the array.

(Figure 1-23)

Nickel-cadmium battery manufacturing and application—the consensus of the power panel was that efforts in understanding completed cell, and so forth, should be somewhat modified into the direction of having more basic studies of what is going on within the cells, actually, the electrochemistry and the electrochemical and physical analysis of just what is happening within the cells, so that we can better understand the cells, better know how to manufacture them, and come out with more consistent cells in the long run. Part of this would lead to less requirements for selection if there is more uniformity in the batteries.

(Figure 1-24)

Substorm plasma effects have to do with the high voltages generated on the spacecraft surface primarily in geosynchronous orbit during the geomagnetic substorm periods.

(Figure 1-25)

The engineering data base is listed as moderate priority. I might say that the way priorities were set, it is very difficult to set anything as a low priority once you have identified problems in space that have occurred. So, when we list high priority, moderate priority, low priority, what we are really talking about is the highest of high priority items and the lowest of high priority items.

This area, which the panel discussion will get into quite a bit further, essentially is becoming a very difficult area, because as new technology comes up, it either is unacceptable for the flight programs because the project managers cannot be convinced that it is ready for flight, or if used on the flight programs, it is used with quite a bit of risk because the new technology item has not been fully characterized and we don't really know how it is going to work.

A case in point might be the nickel-hydrogen batteries. They look good, but we really don't know enough about them to dedicate them as the storage system, the sole storage system for spacecraft. So, development of the data base from the development point of the item over to the flight applications point, what you might call the engineering development, has pretty much been dropped as a research phase or development phase.

The engineering development from the research item to the flight item is kind of missing. When it does come in on a flight project because it is mandatory that we use that new equipment, that new battery, and what have you, the engineering data base is developed for that specific flight project and is not directly applicable to all other flight projects.

(Figure 1-26)

Rotary joint for power transfer—this is transfer from the array to the spacecraft, so you essentially get the power from the solar cells into the main spacecraft itself.

(Figure 1-27)

On array power management was a kind of a blue sky type of thing. There is a need for better management before it gets into the spacecraft, better management of the power in order to keep initial high-power levels down. But, we really, as a panel, could not come up with anything really definitive as to how this would be done effectively. That was the reason it was given a low priority.

(Figure 1-28)

This list of references indicates the breadth of how many papers were presented at the workshop, and these were all done on the first morning or the first day of the workshop. The listing will be in the proceedings in case you want to look at any of them in more detail.

## DISCUSSION

FORD: Lou, I believe, correct me if I am wrong, that there will be a publication out very shortly?

SLIFER: The proceedings will be published. The schedule given out at the workshop called for the proceedings to be published in December. It looks like they are running perhaps 2 weeks behind the detailed schedule. So, to me, it still looks like December. But, it looks like a real possibility for even picking up those 2 weeks. It may be late November, even. The entire proceedings of the workshop, the results from all four panels, will be published at that time.

GROSS: I saw very little relationship between the problems that you identified in the research program and Bob Riebling set forth.

SLIFER: This is really because of the first objective, to look at what has been happening in the past, where are our problems. That is really what we started with. The papers that were presented at the workshop essentially presented the problems that we have been having or that we are having right now.

Bob Riebling's program is directed to the future, 1983, 1985, and as near-term and in the far-term program.

Now, Headquarters has taken a very serious look at these recommendations. I don't know what they are going to decide about them, but I do know that they certainly are not ignoring them. They are looking at them very closely.

RIEBLING: Sid, I have to agree with you, and I think this points out the gap that we see existing between the technologists and the users. One of the first things that we are doing about it is that I asked to have the panel discussion this morning to attempt to bring together technologists and users and to see if we cannot find a way of bringing these people closer together and narrowing this gap. It is something that we recognize as a problem.

VASANTH: You have mentioned that more basic studies related to reactions within the cells including nickel-cadmium batteries are required. Can you throw more light on what specific areas

you would recommend research activity? Have you had any problems in those nickel-cadmium batteries?

SLIFER: Well, I would have to pass that on to someone who is more expert in the specifics of what is inside the battery and how these chemical reactions take place. Not only the chemical reactions you intend to take place, but also the ones that result from materials that are in there which you really did not want in there.

I think from the panel discussion it really comes out with the electrodes, the separators, and the electrolyte, and all three need better understanding as to the electrochemical and physical processes.

RIEBLING: I would like to add a bit to what Lou just said. It is my personal opinion that many of the flight problems that were discussed at the referenced workshop, the problems lie not necessarily with technology, but rather with manufacturing. There is a difference between understanding the technology or the science of an electrochemical system and being able to reproducibly produce these in small quantities for a small buyer such as NASA.

So it may not always be technology, but it may be production problems in there, and we need again to bring the technologies of manufacturers and users all closer together.

RECOMMENDATIONS OF THE  
OSTA FLIGHT TECHNOLOGY IMPROVEMENT WORKSHOP  
POWER SUBSYSTEMS PANEL  
JULY 31 & AUG. 1, 2, 1979

PRESENTATION TO:  
NASA/GSFC 1979 BATTERY WORKSHOP

L. SLIFER  
11/13/79

Figure 1-9

WORKSHOP PANELS

RADIOMETRIC INSTRUMENTS AND CALIBRATION  
ELECTROMECHANICAL SUBSYSTEMS  
ATTITUDE CONTROL AND DETERMINATION  
POWER SUBSYSTEMS

Figure 1-10

## POWER PANEL

<u>ORGANIZATION</u>	<u>NAME</u>
NASA-GSFC	L. SLIFER (CHAIRMAN)
NASA-OAST	L. RANDOLPH
NASA-GSFC	F. FORD
NASA-GSFC	J. WESTROM
NASA-MSFC	J. MILLER
NASA-LARC	E. KELSEY
WPAFB-APL	R. BARTHELEMY
NRL	J. WINKLER
AEROSPACE CORP.	H. KILLIAN
JPL	M. SWERDLING
COMSAT LABS.	W. BILLERBECK
BOEING AEROSPACE	S. SILVERMAN
FORD AEROSPACE	H. MCKINNEY
GENERAL ELECTRIC	S. PECK
HUGHES AIRCRAFT	J. HAYDEN
MARTIN-MARIETTA	M. IMAMURA
RCA	P. NEKRASOV
TRW	R. SPARKS

Figure 1-11

OBJECTIVES

- o TO IDENTIFY TECHNOLOGY NEEDS THAT HAVE BECOME APPARENT THROUGH A REVIEW OF PROBLEMS THAT OCCURRED ON PAST AND ON-GOING SPACEFLIGHT MISSIONS, (NOT FUTURE POTENTIALS)
- o CONSIDER BOTH SPACECRAFT POWER SUBSYSTEM AND EXPERIMENT/INSTRUMENT POWER SUPPLIES
- o TO RECOMMEND A TECHNOLOGY DEVELOPMENT PROGRAM TO ACCOMMODATE THE IDENTIFIED NEEDS

Figure 1-12

TECHNOLOGY PROBLEM AREAS

1. POWER SYSTEM
2. SOLAR ARRAY
3. BATTERY
4. POWER DISTRIBUTION (SWITCHING, FAULT PROTECTION, CABLES, HIGH VOLTAGE)
5. POWER CONDITIONING ELECTRONICS
6. HIGH VOLTAGE POWER SUPPLIES
7. POWER TRANSFER
8. GENERAL PROBLEMS (DATA, QUALIFIED PARTS, ETC.)

Figure 1-14

APPROACH

- IDENTIFY TECHNOLOGY PROBLEMS
  - PRESENTATIONS (SEE REFERENCES)
  - PAPERS FROM OTHER PANELS
- INITIAL CATEGORIZATION BY AREA
- TRANSLATE PROBLEMS INTO TECHNOLOGY DEVELOPMENT REQUIREMENTS
- CATEGORIZE REQUIREMENTS
- PRIORITIZE REQUIREMENTS

Figure 1-13

INTER-PANEL PROBLEMS

- SENSORS
  - OUTGASSING
  - NOISE
- ELECTRO-MECHANICAL-
  - HIGH VOLTAGE (STAR TRACKER) CORONA DISCHARGE/ARCING
  - SLIP RING - BRUSH TRANSFER
  - DEPLOYMENT AND ORIENTATION
- ATTITUDE CONTROL
  - POWER SUPPLY OSCILLATION
  - ARRAY DRIVE STEPPING
  - ARRAY BLOCKAGE
  - PARTICLE CONTAMINATION IN TUBES AND INTEGRATED CIRCUITS
  - STABILITY OF POWER TO DEFLECTION COILS OF STAR TRACKER
  - COLLECTOR TO BASE SHORT IN TRANSISTOR
  - FLEXIBLE STRUCTURE DYNAMICS
  - FEASIBILITY ----- PRODUCTIVITY

Figure 1-15

## PRIORITY LISTING

### HIGH PRIORITY (NEW)

- \*ANALYTICAL MODELING
- \*STATE OF HEALTH MONITORING
- NEW COMPONENT DEVELOPMENT
- HIGH VOLTAGE TECHNOLOGY

### HIGH PRIORITY (INCREASE EMPHASIS)

ARRAY/CELL TESTING

### HIGH PRIORITY (MODIFY)

\*NICD BATTERY MFG. AND APPLICATION

### HIGH PRIORITY (CONTINUE)

SUBSTORM PLASMA EFFECTS

### MODERATE PRIORITY

\*ENGINEERING DATA BASE

ROTARY JOINT FOR PWR TRANSFER

### LOW PRIORITY

ON ARRAY POWER MANAGEMENT

Figure 1-16

## INTERDISCIPLINE DEFICIENCIES

LIGHTWEIGHT STRUCTURE (ARRAYS)

THERMAL CONTROL (BATTERIES)

Figure 1-17

\* ANALYTICAL MODELING

RECOMMENDATION:

1. DEVELOP AC MODELS FOR POWER SUBSYSTEM COMPONENTS
2. SYNTHESIZE ANALYTICAL MODEL FOR POWER SYSTEM
3. DEFINE NECESSARY PARAMETERS FOR ELECTRONIC SIMULATION OF AC SOLAR ARRAY MODEL

RATIONALE:

VERY LITTLE AC DATA AVAILABLE FOR COMPONENTS AND SYSTEM

EXISTING DATA NEEDS REVIEW, REVISION, REFINEMENT AND UPDATING

GUIDELINES NEEDED FOR ACCURATE ELECTRONIC SIMULATION

ELECTRONIC ARRAY SIMULATION IS NEEDED - ONLY KNOWN WAY TO "INCLUDE" LARGE ARRAYS IN GROUND TESTS

PAYOFF:

SAFEGUARD AGAINST BUS INSTABILITY

AVOID HARMFUL INTERACTION BETWEEN ARRAY AND FILTER COMPONENTS AT OUTPUT

DEFINE SOURCE IMPEDANCE AT LOAD BUS

SUPPLEMENT INADEQUATE DC ARRAY SIMULATORS WITH MORE ACCURATE AND REALISTIC AC SIMULATION

Figure 1-18

NEW COMPONENT DEVELOPMENT

RECOMMENDATION:

DEVELOP HIGH VOLTAGE - HIGH POWER COMPONENTS

DEVELOP PARTS

DETERMINE SCREENING TECHNIQUES

FLIGHT QUALIFY

RATIONALE:

HIGH POWER LEVELS REQUIRE INCREASED BUS VOLTAGE (150-400V)

NO QUALIFIED HIGH VOLTAGE - HIGH CURRENT PARTS AVAILABLE

PAYOFF:

REDUCED SIZE AND WEIGHT OF POWER SYSTEM

AVOIDS POTENTIAL DESIGN OR RELIABILITY COMPROMISES

SETS GROUNDWORK FOR FUTURE VERY HIGH POWER MISSIONS

Figure 1-20

\* STATE OF HEALTH MONITORING

RECOMMENDATION:

1. DEVELOP IMPROVED TECHNIQUES FOR ON-BOARD MONITORING AND CONTROL OF POWER SYSTEM AND ITS COMPONENTS  
SOFTWARE/HARDWARE TECHNIQUES TO MINIMIZE IMPACT ON DATA HANDLING AND COMMAND SYSTEM GROUND OPERATIONS  
IDENTIFY REQUIRED STATE OF HEALTH DIAGNOSTIC MEASUREMENTS  
DEVELOP SENSING TECHNIQUES AND SENSORS FOR DETECTING PARTIAL FAILURES  
DEGRADATION
2. DEFINE TECHNIQUES FOR REDUCING COMPLEXITY OF MANAGING DEGRADED SYSTEM/COMPONENTS FROM GROUND

RATIONALE:

EXISTING ON-BOARD SENSORS/MEASUREMENTS INADEQUATE FOR ACCURATE DEFINITION OF STATE OF HEALTH  
GROUND MONITORING AND ANALYSIS IS INADEQUATE AND EXPENSIVE  
GROUND CONTROL IS COMPLEX AND SLOW TO RESPOND  
INADEQUACIES AFFECT MISSION PLANNING AND FLIGHT OPERATIONS  
REAL EFFECTS OF ENVIRONMENT ON SYSTEM ARE NOT KNOWN

PAYOFF:

LOWER GROUND SUPPORT COST  
IMPROVED RESPONSE IN COMPENSATING FOR PARTIAL FAILURE/DEGRADATION  
IMPROVED DESIGN CAPABILITY  
IMPROVED MISSION OPERATIONS  
LOWER POWER SYSTEM COST AND WEIGHT  
SIMPLIFICATION IN C & DH SYSTEM

Figure 1-19

HIGH VOLTAGE TECHNOLOGY

RECOMMENDATION:

1. DEVELOP A DETAILED HIGH VOLTAGE DESIGN GUIDE HANDBOOK
2. DEVELOP A MODEL DETAILED HIGH VOLTAGE PROCUREMENT SPECIFICATION

RATIONALE:

HIGH VOLTAGE SYSTEMS ARE FAILING

LACK OF UNDERSTANDING

LACK OF DATA BASE FOR MATERIALS, ANALYSIS, AND DESIGN/APPLICATION TECHNIQUES

PAYOFF:

INCREASED RELIABILITY AND LIFETIME OF HIGH VOLTAGE CIRCUITRY

PREVENT FAILURES DUE TO LACK OF KNOWLEDGE

BASELINE TESTING REFERENCE PROVIDED

USE OF VERIFIED TECHNICAL GUIDELINES IN PROCUREMENTS

PROVIDES CRITERIA FOR SELECTION, SCREENING, AND ACCEPTANCE OF COMPONENTS

Figure 1-21

## ARRAY/CELL TESTING

### RECOMMENDATION:

CONTINUE (WITH HIGH PRIORITY) DEVELOPMENT OF SPECIFIC TECHNIQUES FOR CONTROLLING PROCESSES INVOLVED IN MAKING RELIABLE INTERCONNECTS/ INTERCONNECTION, FOR VERIFYING INTERCONNECT INTEGRITY, AND FOR PERFORMING ACCELERATED CORROSION TESTING OF SOLAR CELL CONTACTS

### RATIONALE:

CURRENT METHODS ARE LABOR INTENSIVE - TIME CONSUMING AND COSTLY  
METHODS OF VERIFYING REQUIRED NEW TECHNOLOGY ARRAYS (WELDING ON FLEXIBLE SUBSTRATES WITH PRINTED CIRCUITS) ARE UNKNOWN  
RELIABILITY AS RELATED TO MISSION NEEDS IS UNCERTAIN

### PAYOFF:

INCREASED CONFIDENCE IN IMPLEMENTATION OF NEW TECHNOLOGY  
REALIZATION OF BENEFITS INHERENT IN NEW TECHNOLOGY  
HIGH EFFICIENCY  
HIGHER RELIABILITY  
LOWER COST

Figure 1-22

## \*NI CD BATTERY MFG. AND APPLICATION

### RECOMMENDATION:

1. CONTINUE (WITH HIGH PRIORITY) TECHNOLOGY DEVELOPMENT FOR RECONDITIONING AND FOR CELL MANUFACTURING PROCESS OPTIMIZATION
2. MODIFY ON-GOING PROCESS SELECTION AND STANDARDIZATION WORK TO EMPHASIZE DEVELOPMENT OF ELECTRO-CHEMICAL AND PHYSICAL ANALYSIS METHODS

### RATIONALE:

PERFORMANCE OF NI CD BATTERIES HAS BEEN INCONSISTENT AND IS ONE OF THE MOST COMMON CAUSES OF DEGRADED SPACECRAFT OPERATION  
RECONDITIONING HAS BEEN USED TO IMPROVE PERFORMANCE BUT WITH VARIABLE SUCCESS AND IS POORLY UNDERSTOOD  
CELL PERFORMANCE OVER LIFE HAS BEEN INCONSISTENT AND BELOW MISSION NEEDS

PROCESS AND PROCESS CONTROL SUSPECTED  
FUNDAMENTAL UNDERSTANDING INADEQUATE  
IMPROVED UNDERSTANDING WILL IMPROVE BOTH THE MANUFACTURING PROCESS AND THE RECONDITIONING METHODS

### PAYOFF:

IMPROVED BATTERY LIFE AND VOLTAGE REGULATION  
IMPROVED UTILIZATION - REDUCED WEIGHT  
REDUCED GROUND STATION OPERATIONS  
INCREASED PAYLOAD OPERATION IN ECLIPSE  
REDUCED COSTS - REDUCED MANUFACTURING FAILURES

Figure 1-23

## SUBSTORM PLASMA EFFECTS

### RECOMMENDATION:

ENHANCE THE SPACECRAFT CHARGING PROGRAM (CURRENTLY PERFORMED AT LERC)  
BY ADDING DEVELOPMENT OF SPACE PLASMA ENVIRONMENT SIMULATION FOR GROUND  
TESTING OF POWER SYSTEMS TO INCLUDE ENERGY PROFILES, WHERE IT FLOWS, AND  
HOW IT IS DISSIPATED

### RATIONALE:

FAILURES AND DEGRADATION DUE TO PLASMA EFFECTS HAVE OCCURRED  
CURRENT SIMULATIONS ARE INADEQUATE FOR STUDY OR TESTING OF EFFECTS ON  
POWER SYSTEMS  
ACCURATE PREDICTION OF SYSTEM OR COMPONENT PERFORMANCE CANNOT BE MADE  
DEFINITION OF SYSTEM AND COMPONENT DESIGN REQUIREMENTS IS NEEDED  
REFINEMENT AND UPDATING OF ACTUAL ENVIRONMENT IS ALSO NEEDED

### PAYOFF:

ELIMINATE FAILURE MODES OF SPACECRAFT  
DESIGN DATA AVAILABLE FOR SURVIVAL IN PLASMA ENVIRONMENT  
CHECKOUT OF SPACECRAFT CHARGING PROBLEMS BY ANALYSIS/SIMULATION  
BECOMES POSSIBLE

Figure 1-24

## • ENGINEERING DATA BASE

### RECOMMENDATION:

DEVELOP A DOCUMENTED AND BROADLY DISTRIBUTED ENGINEERING DATA  
BASE ON EMERGING TECHNOLOGIES

### RATIONALE:

TIME GAP EXISTS BETWEEN NEW TECHNOLOGY AVAILABILITY AND THE  
APPLICATION DATA NEEDED TO USE IT ON FLIGHT PROGRAMS  
DATA BASE IS NEEDED FOR NEWLY DEVELOPED SOLAR CELLS AND THEIR  
PERFORMANCE CHARACTERISTICS UNDER MANY DIVERSE EXPECTED OPERATING  
AND ENVIRONMENTAL CONDITIONS  
NICKEL HYDROGEN CELLS MUST SIMILARLY BE CHARACTERIZED  
IN ADDITION, RECONDITION METHODOLOGY AND MAINTENANCE DURING  
DORMANT PERIODS MUST BE ESTABLISHED  
APPLICABLE DATA ON SUCH POWER RELATED DEVICES AS POWER MOS  
TRANSISTORS, MICROPROCESSORS, AND HIGH VOLTAGE COMPONENTS IS  
REQUIRED IMMEDIATELY TO PROPERLY APPLY THESE COMPONENTS

### PAYOFF:

FEWER MISTAKES AND FAILURES IN THE APPLICATION OF NEW TECHNOLOGY  
AND DEVICES  
MORE RAPID TRANSFER OF NEW TECHNOLOGY INTO ONGOING PROGRAMS  
INCREASED COST EFFECTIVENESS AND SCHEDULE CONFIDENCE IN THE  
UTILIZATION OF NEW TECHNOLOGY

Figure 1-25

### ROTARY JOINT FOR POWER TRANSFER

RECOMMENDATION:

DEVELOP A COMBINATION ROTARY POWER AND DUPLEX TRANSFORMER CONFIGURED TO PROVIDE FOR HIGH POWER AND HIGH DATA RATES WITH INCREASED RELIABILITY AND REDUCED NOISE

RATIONALE:

MECHANICAL SLIP RINGS CONVENTIONALLY USED

SLIP RING PERFORMANCE WILL NOT INSURE RELIABLE DATA TRANSFER AT HIGH DATA RATES

SLIP RINGS AND NEWLY DEVELOPED ROLL RINGS HAVE CHARACTERISTIC NOISE AND VOLTAGE DROP MODES

ROTARY TRANSFORMERS, WHICH HAVE BEEN PREVIOUSLY USED FOR TRANSFERRING MULTI-CHANNEL DATA ACROSS A ROTARY INTERFACE IN BOTH ANALOG AND DIGITAL FORM WITH A MULTIPLEXER FOR TRANSMISSION AND DEMULTIPLEXER FOR RECEPTION, ARE NOT CURRENTLY CAPABLE OF OPERATING AT FREQUENCIES BEYOND THE 15 KHz RATES

PAYOFF:

LONGER LIFE

HIGHER RELIABILITY

IMPROVED DATA RETURN QUALITY

HIGHER DATA RATE

Figure 1-26

### ON-ARRAY POWER MANAGEMENT

RECOMMENDATION:

DEVELOP COMPONENTS/DESIGNS TO PROVIDE BASIC POWER MANAGEMENT ON THE SOLAR ARRAY RATHER THAN WITHIN THE SPACECRAFT

RATIONALE:

VARIABILITY OF ARRAY POWER OUTPUT RESULTS IN EXCESSIVE REQUIREMENTS FOR BOTH ELECTRICAL POWER CONTROL AND THERMAL CONTROL SYSTEMS TO ACCOMMODATE

PAYOFF:

SIMPLIFY POWER SYSTEM

REDUCE THERMAL CONTROL REQUIREMENTS

Figure 1-27

## REFERENCES

1. Slifer, Luther W., Jr., "Power Technology Improvement Needs Identified From GSFC Spacecraft", NASA Goddard Space Flight Center.
2. Barthelemy, Robert R., "Spacecraft Power and Experiment Power Supplies", Air Force Aero Propulsion Laboratory.
3. Killian, H.J., "Input to Spacecraft Power Panel, NASA Technology Improvement Workshop", Aerospace Corporation, 29 June 1979.
4. Billerbeck, W.J., "Spacecraft Power Supply Technology Needs", Comsat Laboratories.
5. Briggs, D.C. and H.N. McKinney, "Spacecraft Electrical Power Supplies and Systems Technology Needs", Ford Aerospace and Communications Corp., 22 June 1979.
6. Westrom, J.L., "High Voltage Failure Tendencies in Instrument Power Systems", NASA Goddard Space Flight Center.
7. Nekrasov, Paul, "Payload and Power Subsystem Electromagnetic Compatibility", RCA Astro-Electronics.
8. Miller, J.L., "Power Subsystem Flight Technology Improvement Requirements", NASA Marshall Space Flight Center.
9. Hayden, Joseph, "Spacecraft Power and Experiment Power Supplies", Hughes Aircraft Company.
10. Winkler, James G., "Four Satellite Power System Case Studies", Naval Research Laboratory, 18 June 1979.
11. Swerdling, Melvin, (untitled; discussion of five JPL spacecraft problems), Jet Propulsion Laboratory.
12. Silverman, Sidney W., "Identification of Technology Needs", Boeing Aerospace Company.
13. Ford, Floyd E., "TIROS-N Power System Anomaly", NASA Goddard Space Flight Center.
14. Sparks, R.H. and P. Goldsmith, "Spacecraft Electrical Power and Distribution System Technology Deficiencies", TRW Defense and Space Systems.
15. Peck, Steve, (oral input; discussion of high voltage design in power systems), General Electric Space Division.
16. Randolph, L.P., "Spacecraft and Instrument Power", NASA Office of Aeronautics and Space Technology.
17. Imamura, Matthew S. and Arthur Bridgeforth, "Automated Management of Power Systems", Martin Marietta Corporation (Imamura).

Figure 1-28



PANEL DISCUSSION: BRIDGING THE GAP  
TECHNOLOGY DEVELOPING  
FLIGHT HARDWARE

Chairman, F. Ford  
NASA/GSFC

I would like to welcome each and every one of you to Goddard Space Flight Center. I think this is the 11th year that we have had a meeting here on batteries and the 10th year officially where it was called a workshop.

I would like to know how many are here this morning for the first time. Would you just raise your hands. Well, that is quite a large percentage of the group. I hope you enjoy the workshop. We try to vary the format from year to year, and this year for reasons stated earlier, we have a panel discussion.

Lou Slifer has given you the background on the OSTA workshop that was held this summer. There were four different disciplines discussed at this workshop. They were power which Lou has covered, electromechanical, attitude control, and radiometric instruments.

It so happened that the initial call for the workshop was on radiometers or radiometric instruments, but because of ongoing flight spacecraft, different problems with different missions, it was decided to expand the workshop into the other areas. As with the design of the satellite, the last thing thought about was the power system workshops. So, we somewhat got into the tail end of it.

Having been a participant in that workshop, it was very worthwhile. We found out that we are not flawless, we do make errors in design and we make errors in judgement. But, the proof of how good a technical group we are is to learn from these past mistakes, and that is what the workshop was all about.

To further that discussion, I have requested people from private industry and government labs to sit in and to assist me in establishing a dialogue with the people in the battery community, particularly defining the problem, trying to come up with some recommendations, and bridging the technology gap. Out of these four workshops, there was one very common theme: that is technology gap. Or, better said, the lack of engineering data base. Where is the line drawn between R&D laboratories saying, yes, this is developed technology, and the project manager saying, yes, we are ready to fly?

What is very real is that there is a large gap in that area. We find that, and I am sure most of you have been in this situation, you have something that looks good, you follow it from development for 4, 5, maybe even 10 years, and you sit down with a project manager and say, "We think this is what you need for your mission. It has the peculiarities necessary to solve your problems."



Then, I have Gert Van Ommering, Ford-Philco, Ford-Aerospace almost at Comsat. Gert comes to us with kind of a mixed background, so I think he can speak from either side of the subject.

Ed Kipp, TRW. Ed's background is in aerospace batteries. He has been in it for a number of years. He works off in the manufacturing and applications end.

And, of course, Dr. Dave Pickett, TRW. I am sorry, I knew I was going to miss one this morning—Hughes.

With that I have asked each panel member to be prepared to give us a 2- to 5-minute discussion of his viewpoint on the issue.

After the panel members give their viewpoints, we will then open the discussion for questions and general dialogue from the floor. I encourage and will seek your participation. Steve, I would like for you to initiate the discussion, if you would.

## DISCUSSION

PADDACK: I have the uncomfortable feeling that I am the only member of the user community group. I use your batteries, and a lot of the things that Floyd was saying really rings true. We find ourselves in very awkward situations. I have dealt primarily with missions that are made here at Goddard, so I am more familiar with in-house projects than I am with the projects that are made out.

We find ourselves in a situation in which we want to fly a real good spacecraft for nothing. Like, reduce the cost to practically minimum. You would like to develop new technology, but they say, "Take high risks. But, if you fail, you are in trouble." That is the vice. They want success, they want to keep the manpower costs down and the hours cost down, and it is a very difficult situation.

Everybody gives a lot of lip service to new things, where we often find ourselves in situations in which we would like to fly things and try new things. The remarks that Ford was making about the engineering development phase, the data base and the information, we find ourselves in a situation often in which a new technology, a new thing, a new device we would like to be used in a spacecraft, and the project officer says, "Has it flown before?"

And the answer may come back, "Well, not really. You know, we have changed it a little bit, we have got this new thing called a lithium battery, and it is great." Or, "silver hydrogen," or whatever.

We say, "Well, good, we will talk about it and maybe develop some kind of a phase." Then we say, "We would like to test it" and the manufacturer that produces the battery wants to test it and will say, "Here is our environmental test program."

We will say, “We would like to test it like we fly it.” But, we find for a variety of reasons we cannot do that, and we cannot test it like we fly it, so we go off with a pretty substantial risk. It makes us very nervous to fly new technology from that point of view.

I don’t know what the solution to this kind of problem is. I have been involved with cases where we fly new technology, and I guess a case in point is related to solar cells. We had to have a new spacecraft, the whole surface of which was conductive. Well, that is kind of a bizarre thought to start with. How do you handle a totally conductive surface of a spacecraft?

Well, they get the solar cells and the antennas; the whole thing starts developing. In particular, with the solar cells—and I see Dr. Gaddy smiling up there—he was put into it up to here, and we did not know whether it was going to work. But, we had to put the cover on these solar cells to transmit charge from one place to another. We were not talking about much charge.

But, we were finding that the stuff that we coated the cells with changed its characteristic. It was not always the same resistance. Then, we had to tie each solar cell to the next, and we would run into such simple problems, the kind that you would run into at home with your kid at dinner time.

You would give Mark his glass of milk and you say, “Don’t spill it. You spilled it last night.” He reaches over and his coat sleeve knocks over his glass of milk. You say, “Spilled your milk again.” And you get angry.

Well, this happens with the spacecraft. We have technicians who wear lab coats, and we say, “Look, delicate stuff, don’t touch.” Lab coat drags across the solar cells and breaks the little conductive wires that connect.

These are the kinds of things that rather get you. You cannot test something. You want it to be a success, and when you are all done, you look through your development program, you say, “What do we have?” You say, “Well, I have got a battery I think is going to work, and I have a system that looks good.”

Readiness Review Committee says, “Let me see your test program.” You know it always comes back to that thing. And you say, “If we had a few more dollars.” You don’t get a few more dollars. “If I had some more time.” You don’t get more time.

It is really a tough problem. It reduces to the thing where we would like to, from a conservative point of view, go down to Sears and buy a Diehard. Look, we got a 5-year guarantee. It is kind of like the conservative person.

But, on the other hand, the big panacea comes, shuttle. We have got his wonderful shuttle that is going to solve all our problems. Weight is no problem. All of a sudden, weight is a problem. So, we are pressed back into weight. They keep nibbling away at us. We feel very uncomfortable with it.

Would we like to find new technology? Yes. I would like to do it here at Goddard. I would like to see new technology flown on the spacecraft here at Goddard. I was encouraged to see that Fred Betz has got nickel hydrogen into orbit. I hope it works.

BETZ: I cannot do it alone.

PADDACK: However, that is the kind of thing that we are into. It is a trap. It is a dilemma situation.

BETZ: It is funny. I think I missed only one of these workshops and that was the first one, so I have been here a long time.

This is not a new problem. It was a problem when I was working with batteries 10, 11, and 12 years ago, getting new technology on. And the problems have been the same: It is developing the data base.

We, at NRL, together with Comsat Labs, did get nickel hydrogen flying without a data base, without a voluminous data base that is required for most programs. We did it with a backup system with nickel cadmium to back up the nickel-hydrogen system. So, that made it relatively easy.

Also, I represented the project officer at the same time I represented the people responsible for the power system, so we could do pretty much what we wanted to do. We had that kind of flexibility in our organization.

Comsat Laboratories had developed the technological element, and we, together with Comsat, aggressively said, "Hey, we want to fly this stuff." It was not a case of the project office saying, "We don't want to fly it." Or, "We are afraid of it." We went after it aggressively, and that is the difference.

However, when we proposed NTS-3, we said, "Let's leave the nickel cadmium battery off. If we are going to fly just nickel hydrogen, we are going to make it failure-proof. We will put bypasses on the cells." And our management said, "Wait a minute. The last one worked so well, we are not going to change it." NTS-3 got cancelled.

But it is amazing how the inertia of the system developed through one program. "You flew nickel hydrogen, fly it again, but fly it the same way, don't change anything." And money came into the picture. We did not have the money to run a new development program for bypass.

I think that new technology will come in where it is mandatory. The Galileo program, perhaps, will force the lithium system into spaceflight. Where the needs are mandatory, yes, you will get it; where the needs are not mandatory, alternative approaches today seem to be the way to go.

Now, the only way around this that I see is for the organizations that do technology development sponsor it. The organizations that launch spacecraft which are the same organization, primarily the Department of Defense and the Air Force—pardon me, the Air Force and the Department of

Defense—and NASA, who do the technology development and end up primarily responsible for flying spacecraft to force the issue in technology development. I will propose that those people target these new developments directly into their future programs and force them along.

You are saying that there is a cost benefit in the future for these programs, for this new technology. The cost benefit is in the future. The corporate payoff is in the future for NASA and for the Air Force. But, you guys don't want to invest the dollars for the program manager to bring it along into his program. He says it costs too much and it is a risk.

Take the risk out by funding the development from the technology right through the flight, to the flight on a given program. Then you have bridged the gap.

KIPP: When Floyd asked me to sit on this panel, I somewhat got to reminiscing, because I can go back to about 27 years into the mid to late 1950s when we started in the early ballistic missiles programs at the General Electric Company. When I started thinking about this and thinking about the change in atmosphere and the climate that has taken place between those days and what we are looking at today when it comes to flying hardware.

I am sure that anything that any one of us will say here today will be an oversimplification of what the problem really is. When each of us in his own way and in his own shop tries and finds ways of convincing program managers to fly different kinds of hardware, it seems as if we had lost some of the spirit of adventure.

Back in those early days, it was not a matter of having to develop so much of a data base. It was finding something to fly. Finding someone who could make something that you thought might work.

Well, we did. Earlier our goal was, "If I can get something to fly for 3 months, that would really be neat." We found something that would fly for 3 months. Then, we flew 3 months, it lasted 6 months, it lasted 3 years, and we were very elated.

Also, in those days, there was lots of money available. Program managers at that time were not so profit-oriented as they are today. They were success-oriented, as far as getting something that would fly, and fly and last for 3 months or 6 months.

Today, the climate is totally different. Speaking from the commercial end of the world if you will, at TRW, where we are in the business to make a profit and to have successful programs, the climate has truly changed. Today, you have to be a darned good salesman to convince a program manager that what you are proposing will work and that it will work successfully.

We have gone through this stage where we have been flying nickel-cadmium batteries for the most part in supporting low-Earth orbit and geosynchronous kind of orbit missions, and we have got them working for 5 years, 6 years, and in the area of 7 and 8, even though there have been a lot of problems come along when we get to the 6-year and 7-year point.

As Fred said, it has been working, you face a program manager with a silver hydrogen, nickel hydrogen, or something else, and he says, "Prove it to me fellows. You know I got something that works; I know it worked for 7 years or 6 years." You have got to be a darned good salesman in today's climate. You have got to start your selling very early. You have got to sell. If you are working with a government agency, try and sell them on the idea that it is a feasible idea; if you develop the necessary data base, it will work. You carry your selling right along.

You sell in-house people; you sell your own functional management to get the money to start something, to develop the data base, to buy the hardware; and then you start working on the program manager end of it.

Right from the beginning to the end it is a matter of convincing someone that it is a good idea, that it will work, and that the payoff is there.

PICKETT: Along the same lines, I would like to mention that in selling the technology sometimes you get so enthusiastic about it, sometimes it is oversold a little bit, and it is sometimes hard to live up to the expectation once you get some real test data on the article.

It is very difficult to develop a data base for new technology. Most program managers want to see real time, live testing on the component or cell that you are trying to introduce into their program. This is not always possible. By the time you get the real-time test data on the thing, the technology is almost obsolete to satisfy some people anyway.

Really what is needed—the Air Force and NASA have recognized this for quite some time—is accelerated testing, so one doesn't have to go through the arduous process of going through the real-time test every time you want to put a new battery, cell, or whatever it is on the spacecraft.

We, at Hughes, are still continuing in this line. We have got some accelerated testing going in our R&D, and we continued to watch with interest the research that goes on with the NASA program.

Accelerated testing has got a bad name in the Air Force to some extent. When I was with Wright Patterson, it was very difficult, if not impossible, to sell anybody on an accelerated test program for nickel-cadmium batteries. It was only with NASA's cooperation that any kind of a sizable program was developed and proceeded with.

Generally, everybody uses accelerated tests. But trying to get government agencies to fund them, because of all the money that has gone into it, is sometimes difficult.

Changing the subject just a little bit, my experience, mainly with new technology, is trying to introduce electrochemically impregnated plates into nickel-cadmium batteries. That's where I started out.

If the nickel-hydrogen system had not come along, we might still be struggling with it. But, it was found out that this type of electrode was ideal for the system. The point I am trying to make

here is there has to be a definite need. We have to have some kind of driving force to get the new technology into a system. Just because it is an improvement, it will not happen. There has to be some type of driving force or basic need to get it done.

MASSON: I guess I would like to make a couple of the same points that Fred did.

When you are trying to make a transition from the new technology, any kind of new technology toward flight hardware, there are a couple of different paths you can take, ranging anywhere from government or industry-funded R&D efforts, to direct funding by the user program.

Of course, the path you take depends on awful lot on the technology that you are looking at. Technology has to be evaluated in terms of the potential benefits, development costs, and the risk. If the potential benefit of a given technology becomes essential to meet the basic requirements of a particular program, then, in a lot of cases, you can expect the program to pick up the responsibility and the cost of funding that technology development up to flight status.

A good example of that kind of development effort was the development of the battery in the Viking program. By international agreement, there was a requirement that the Viking spacecraft had to undergo heat sterilization at 135°C before launch to prevent contaminating the Martian environment. The Viking program undertook the development of a nickel-cadmium cell that was heat sterilizable and was successful, I might add. Those cells are still operating after 3½ years on Mars.

The same kind of technology development that is funded by our program organization might be applicable, as Fred mentioned, to some of the new lithium systems in which the stand life, or the extremely high energy densities that are potentially available, might really become essential to meet some of the new requirements.

Other kinds of technology development, such as improvements in nickel-cadmium systems or the development of metal-hydrogen systems, face a little bit different problem. In a lot of cases, their application is not essential to a given program, so the program will tend to evaluate those in terms of potential benefit versus risk. And, in a lot of cases, what they are doing is competing with existing "flight-proven" hardware designs. That becomes another kind of a problem.

I guess the point of all this is that there are a couple of different ways to get from a new technology system to flight hardware, and you really have to look at the individual technology to determine what the right path is for that development. In some cases it is easier than others, and again it depends a lot on how necessary or how much a given program hinges on that technology.

VAN OMMERING: I would like to use my few minutes to illustrate this whole question with an actual example that I am involved in at Ford Aerospace that has to do with bridging the nickel-hydrogen gap.

They have taken a system here that has been proven in the lab quite a few years. As we heard earlier, Fred Betz had the guts to put it on NTS-2, and it is working there really well. So, we are

looking at a situation in which we have a reasonable data base that allows us to seriously consider doing something like that on an actual working commercial spacecraft.

Fortunately, Intelsat decided this was the time to do it, Intelsat 5, for some late problems and other improvements that we would like to see, particularly in the lifetime of the spacecraft. It was decided in the middle of the Intelsat 5 program that we were going to try to introduce nickel hydrogen as a sole energy storage system on the spacecraft.

Now, Intelsat took the approach of making essentially a near-zero risk situation. We are now involved in a program of developing nickel-hydrogen batteries for Intelsat 5, but at the same time we are committed to building nickel-cadmium batteries right alongside it for the same spacecraft that they are going to put nickel hydrogen on.

That's rather an interesting situation because it takes a bit of the pressure off the schedule requirements. If nickel hydrogen has some technical problems that you still need to solve, we have the option of slipping it on the spacecraft and using nickel cadmium.

It also takes the pressure off entirely in the area of technical success. If a real snag develops, you have the backup system there and you can put it on the spacecraft at a fairly late stage, a few weeks before launch.

So this is really an ideal way to bridge that gap. All that it takes is a lot of money and a lot of confidence on the part of the eventual spacecraft user. I think, in the case of synchronous spacecraft, the payoff appears to be large enough in terms of added years of operation and added general reliability, as well as the weight advantage that we have in nickel hydrogen, that it is worth the \$5 to 6 million that Intelsat has pumped into this program or is going to pump into this program and bring it on line.

When you consider the payoffs once you get into Intelsat 6, 7, and on stage, I think a general approach to this new technology is to look at those benefits very simply in cost terms. If we can lay some money on the line right now in the development of a usable spacecraft stage, there are tremendous payoffs in the long run.

In some cases that may not be true, and I think that has got to be based entirely on that sort of an argument.

**BADCOCK:** My comments are really from the end user. You have something that has been developed, and you have to find someone that has the need. Having done that, you have a sponsor. I am going to address some of the questions that sponsors are going to ask and expect to have answered. All of these are, again, motherhood statements. They do have a lot of bearing on how happy he is going to be with whatever your new development is, and he is willing to pay for it.

I guess the first thing is, you know he needs it, that is why it is there. He should understand that he is going to buy the pain that is involved in bringing this new development on line. It is not the same as the last one, it is new. There are going to be a lot of little things around that are going to give you at least intermittent grief.

So, what does he expect to see? Well, we have talked about the demonstration base. That is very important. But included in that you need to be able to demonstrate what it is going to play with the rest of the system, whatever it is. If you have a battery that works well, why you should also be able to demonstrate that it is going to interface with this system properly. So, between the system and the batteries, they are not going to kill one another, either immediately or several years downstream.

The sponsors also should ask for the failure mechanisms, and you should be able to tell them. You cannot say, "Oh, it doesn't fail." You should be smarter than that. So, you should define these failure mechanisms. You know how it is going to fail, but still it is a better product.

I guess the two final things, early in development you want to start talking about are aerospace quality specifications. It is your development, you built this, you built that, and so on. But, as you come along, you really should start considering aerospace or flight quality specifications to be written in the program and things to be built to that, and not let it come after the fact. This adds costs. All these things add costs, but they are really important if you want to demonstrate to the end user that he should buy your product.

Along the same line, you want to get a manufacturer into this. If you are the manufacturer, great. But you want to get the manufacturer into this at an early stage, so you can demonstrate you can make a lot of them, or as many as are needed.

Other than that, I think those are the kinds of things that you wish to get from the standpoint of the guy who is going to use it in the end. These are the things he wants to see to demonstrate that this is a better mousetrap, or whatever.

NAGLIE: Let me go way back. I represent the technology end. Our workhorse system, the nickel-cadmium system, has not yet been characterized from the inside to the point at which you can design a battery for a particular mission.

In the beginning, they flew many NiCad cells for 20,000 cycles at very shallow depth in low-Earth orbit. There comes a time they put it in synchronous orbit, and they got into trouble. Why? There is no actual data base system from the standpoint of how the electrodes are impregnated, whether they are impregnated fully or shallow, or what kind of current densities any particular electrode will stand.

The batteries themselves are not designed for the mission. Even in the workhorse system, the nickel-cadmium system, we do not have that data base.

The technology end of it has not developed it, and it is not that hard a thing to do. It has been rejected back in the 1960s several times, and I am mad about it, of course. But, let us go on to future systems.

I still think we need the NiCad data base, and we should develop it for any given method of impregnation in the electrodes and any given method of making the electrodes. It is only a matter

of doing the work and building a character box. All right, we are going to fly this mission; therefore, we need this nickel electrode, this cadmium electrode, and this separator.

Probably it is as extensive as the accelerated testing program, but it still is not available and it should be if we are going to fly NiCads.

Now, going back to getting the program manager to accept new technology, in the NASA organization, we failed several times with new technology. We failed the silver zinc getting on the Viking. That was a little problem with economics. We do have a silver zinc cell. Some of them are still alive now after 11 years being sealed and sterilized. It is a new separator development that we worked out at Lewis.

The thing that has to happen for new technology to get on a mission is at the time, even before the mission is approved, when it is conceived with mission analysis people, the technology people have to be informed of it and develop a parallel technology program so that they have the data base. When it is approved, now they have the data, and they can convince the program manager that this is the electrical storage system that should go on a spacecraft. It takes a lot of data to convince the program manager. Not just the NASA program manager but the industry program manager has to be convinced.

KILLIAN: As technologists, we work on new technology for a long time to try to get it into spacecraft. As has been pointed out, the program managers are reluctant to receive it. So, we think, my God, something is wrong and we should be doing something else. I would like to inject the thought that perhaps nothing is wrong at all and that we are perhaps more enthusiastic than we should be. It is just nature taking its course. It is difficult to get these things into the spacecraft.

I would like to quote a famous saying by Lou Gomberg at RCA. He had an Air Force DMSP program. He says, "Better is the enemy of good." Whether he is correct or not is based on a lot of experience. So, I would just like to inject that thought. Perhaps I don't think it is wrong at all.

GROSS: I would like to say amen to the remarks of Bill Naglie, and perhaps restate some of the things he said and build on what he said a little bit.

Certainly, making the transition from old technology to new technology has its own set of problems. But, in general, they are usually able to get this work properly funded. Possibly not at the rate we would like, but we are usually able to get new technology aboard. The problem is to avoid making the same mistakes in new technology that have been made in the past.

The nickel-cadmium system, for example, has been in space for 20 years, and we know very little about it. We do not at this time have any formal methods to characterize electrodes for this system; we cannot tell good from bad; and we cannot find any way to determine if electrodes made from one batch are the same as another batch. But we have many problems with this system continually failing prematurely. And, year after year, the government research decisions take the view that the nickel-cadmium technology is a developed technology, it is established, and there is no need to spend more money in this area. So, very little research gets done.

The Air Force, for example, sponsored Dave Pickett's work. But, right at the point when he got to start learning a lot about it, they cut off the basic research.

NASA Lewis people have always said that more basic work is required in the nickel-cadmium area, but they have never been able to sell it to get it sponsored. It has not been recognized as an important area.

I am pleased to see Lou Slifer's summary today, pointing out the great need to get more basic understanding of this old system. With regard to the data base, the data that is needed is not simply cycle life data, but it is also basic understanding of the old system.

OTZINGER: With regard to the data base, a lot of companies have, I think, their own data bases that they consider to be somewhat proprietary. I think there is a data base. Unfortunately, it is not generally available.

One thing that maybe would pay off in a workshop much like this one is that we could identify some of the kind of characteristics we are looking for in R&D. You could have people present papers pretty much one area, and the data base becomes generally available.

I think, my comment there again, there is data around but it is not accumulated by any particular source. What is needed is someplace where everybody can go to say, "This is our data base, an agreed-upon data base."

No one wants to believe anyone else either. We do our forecasting in our lab and say, "Well, it means something over there, but you know we don't believe everything they do."

So I think, if we could bring up data here in a particular area, say nickel hydrogen, for example, cycle life, each year we would have four or five companies all testing. Like the Air Force, they have Applied Physics Lab (APL) WPAFB, and made cells available to a lot of different companies to test. Now, if each one of those companies were to test somewhat the same area and then present the data, we could sift through it and say, "Okay, this is what we agreed is the acceptable data base."

Another comment is that with regard to flying things and saying, "Well, we have flight history." I think we have an opportunity in the near future of putting experiments on the shuttle and actually conducting tests, going up there and having a dedicated test that would demonstrate the feasibility, demonstrate that you have a workable system.

I suggest this now to the NASA and to the Air Force, to people that present the money for this kind of R&D work.

Now, as I say, that is a suggestion and that would be one way that you could get on lithium. You would get some of the more controversial systems up there, you could get some data, and everybody could see where you are.

KIPP: I think Burt has got a good comment when he talks about the fact that we all do our own thing.

I have been coming to these workshops for a long time, and I propose we have another gap: the gap I see is the gap between people and all the different government areas and industry doing their own thing, but having a reluctance to sharing that information with everyone else.

I think we need more different kinds of meetings where we can share that information and find out how we get people to break down the reluctance to share that information with everyone else. We all do have a common purpose, but we seem to have a reluctance to share that information.

BARNARD: When you take these high risks, who carries the can? Where does the warranty come in? Is it the responsibility of the company if something goes wrong with it, or does the user pay?

BETZ: The user pays.

FORD: I think the answer to that could be twofold. But, yes, ultimately, the user does pay and the user, meaning a satellite program that has invested its resources and is willing to take a certain amount of risk. Then, once the satellite is up there, you have found out the emphasis of resources and risk was somewhat out of perspective apparently, because the risk somewhat overshadowed all the spending you did to get a successful satellite.

I might point out that I think a point we made earlier about the changes in environment, that in the early part of the program we were looking for something that worked, and today we are dealing with, primarily, two classes of satellites; those that are operational satellites that are put up there for scientific purpose. The ones most familiar to you in the audience are the weather satellites that are put up there and they are operational. They want low risk, they want cheap satellites, but they want a 10-year mission.

Now, talking about the other satellites which are scientific in nature, they are very much research oriented as the Viking program and some of the astronomy programs. And these program managers recognize there are risks that can be taken, but they usually are willing to take the risk in the instrument field, not in the spacecraft field, not in the design of components for the spacecraft.

SEITZ: Fred Betz, you mentioned the Galileo program with forced lifting into spacecraft. I am wondering what were the requirements in the Galileo program to do this, and what sort of lifting systems do you see?

BETZ: I would like to pass that one since I am not personally involved in the Galileo program. Dave Pickett is probably familiar with that, and I will pass the ball to him and let him tell you.

PICKETT: I think the reason is simply that the state of the art in batteries just would not suffice to complete the mission.

Now, as far as the batteries themselves and that type of thing are concerned, we have a gentleman here from Honeywell who is going to talk about the cells and that type of thing later on in the program.

That is the best answer I can give you in a nutshell. Stan Krause has been running the Galileo program at Hughes. I have not been involved with it. When I took over as head of the section, that program was split out with Stan paying personal attention to it. So I haven't had the opportunity to spend the detail with it that I would like to give you a more specific answer to your question. But, you can talk to Stan, and he can fill you in on the details.

LEAR: I would like to voice a couple of comments that the panel had brought up about the low risk in the NiCad system, and also the low cost of flying a NiCad system on board the spacecraft.

You have to be a very good salesman nowadays when you are working proposals for spacecraft applications. You go to your program manager and say, "I would like to run an on-line test for a peculiar situation we are in," or the test that is required to substantiate flying a spacecraft in that particular orbit that you are working on.

Because of the data base that we are supposed to have with the 20 years of background testing and all that we have done on NiCads, the program managers are not willing to support our cases now, and they say, "Well, new technology is coming along. Nickel hydrogen has got a zero data base. But we have got NiCads that have got 20 years. So, we don't need to run a test."

Therefore, the cost is out. No more testing. You have got a data base. So, we have to educate the program managers as well as the customers because he is also trying to cut down when you are substantiating a data base.

HALPERT: When the technologist attempts to sell his product to management, he has to speak from a position of strength. I will have to allude to another gap that we have, and that is between the scientist and the technologist.

There are 100 papers on the nickel-hydroxide electrode, and yet we don't go back into the basic data to understand how the nickel electrode is working. All we want to do is keep testing the batteries, keep testing the cells.

It is understandable how some of the project managers can look at that and say, "My God, another test program. What are we going to get out of it the next time we buy it as something new?"

So, I think we need some interpretation of people from the basic sciences, the guy who is working at the microelectrode level on up to the hardware item, to extend that technology or to extend that science to the technologist so that he can then speak from a position of strength.

NAPOLI: Among the users and manufacturers of various agency representatives that we have here, there is a wide data base of nickel-cadmium cells that exist, and there is also a wide variety of types of cells that have flown. So, you have a big choice of cells in the data base to look back on in history. I think you will find if you look at the various programs, Air Force and NASA commercial programs, you will find that some cells are performing better than others.

What I haven't seen come out, except at a last SAMSO workshop, is that there was a general agreement as to what should be done to improve the longevity and reliability of cells. I don't see coming out of this, particularly the Goddard battery workshop, people getting together and saying "Look, that company, that group, or that agency did something right. What did they do that is different?"

Okay. "Why don't you try to investigate that, and if they are doing something that is right, how come we cannot do that?"

I think the problem why that does not come out is the old "NIH Syndrome" that seems to prevail throughout the industry. Not only is it an "NIH Syndrome," but there is also a feeling of pride and sensitivities in some of the programs that exist. One company does not want to exchange data with another company. There are many users here who just don't want to show their data until maybe 8 or 9 years after the program is past and gone.

So, I think the problem you have to overcome is the "NIH Syndrome," for one thing. If GE has a power system, TRW has a power system, and Hughes has a power system, some way you will see some of those power systems – when I say "systems," it is ultimately a system problem – are working better than other spacecraft or other programs. And yet, someone does not go back and say, "What are they doing different?" "How come we don't do that?"

Again, it is the old NIH problem. So, I think we should all take a little bit, sort of an in-depth look at what we can do to change that. Unfortunately, it is beyond us on the working level. It is more on the corporate level that you have these resolutions come to a head.

GASTON: I heard the comment made by several gentlemen this morning of use of accelerated testing to build up a data base relatively quickly.

I am all for that. I would like to caution people. You have to be able to correlate it with real-time factors, degradation rates, and so on, because there have been some real wrong conclusions drawn based on accelerated testing. We have to understand the mechanisms which occur and possibly correlate them with the component degradation inside, or compare very carefully with real tests, because that is a dangerous road.

SCHULMAN: I would like to propose a question to the panel. You know we hear quite a bit about battery anomalies. Unfortunately, the only channel most of us hear about these is through the channel of industrial gossip.

With all these battery anomalies that seem to exist, I would like the panel's opinion as to whether they are caused by an inherent fault within the nickel-cadmium battery itself, or an inherent fault with the system engineer who has applied his experience to the utilization of this battery.

FORD: That is a big task. Which of the panel members would like to field that?

BETZ: I will take that. Irwin, you have really got a good question there. But let me say this: Somebody mentioned very early in the session, I think it was Sid Gross, who said that years ago we flew batteries and they got 20,000 cycles on them. And a lot of batteries got 20,000 cycles. They only expected 6 months and they got 18 years, this kind of thing.

What is different between then and now? The batteries have improved; the power systems have improved. The difference is that management thinks we can use the batteries more and more. They are forcing the engineers to 80-percent to 90-percent depth of discharge. They are forcing more cycles at higher depths of discharge, and the battery engineer really has his back to the wall.

That is the way I feel. The battery fails because you push it too far. You have to understand the limitations of the battery because you cannot change the battery. You have to understand its limitations and to work within its limitations. If management pushes too far, it is going to fail. So, we have an anomaly.

KIPP: One thing about Irwin Schulman is that he knows how to ask the right questions. There are many paths for the answer to that question. If you are looking at the military that has a requirement for a spacecraft, one of their requirements is that your exposure to it, your availability to look at that spacecraft and to look at what it is doing is extremely limited.

They want a spacecraft that will fly virtually hands off, so you design systems that will do that job. You work with all the power system people, and you come up with systems that will do that job. Maybe 5, 6, or even 4 years later you will find, "Gee, there is something we didn't look at because we are not all instantly superintelligent. We designed systems 5, 6, and 7 years ago that we thought would do that job. We are finding today. . .," and here are specific references to anomalies. "We are finding we didn't know all the things that we should have known or would have liked to have known about how to use those systems in that kind of mode."

Now, you look at the other side of the coin where you have scientific kinds of satellites, a lot of them are operated by NASA where you can look at them constantly, 24 hours a day. You have on-line programs to look at the data; you have off-line programs to massage the data. In many cases you will not have the same problems with the spacecraft you can look at 24 hours a day, that you have with those you cannot look at.

So, we have more than one kind of problem here that we have to address.

FORD: Yes. In response to your question, Irv, I might point out that at the workshop there was a broad cross section of reasons for the problem. There was no one area that we pointed out that we don't understand the technology as a specific cause. When you look at it, there are many reasons that we have problems in orbit.

One of the things that was mentioned early, and I believe Chuck mentioned this, I believe it should be looked at. This is in light of the data base that we have. We are comparing what we are doing today, what we have done in the last 3, 4, and 5 years, with what we did 10 or 15 years ago.

Sure, there is a whole wealth of information or data based in the NiCad field. But, the question you always have to ask yourself is, "How relevant is that to what I am doing now?"

And that is where the real clincher comes, because you find out that, by and large, there have been changes in the manufacturing process; maybe a manufacturer has totally relocated his plant; and we have people who get involved which also affect the builder's ability to produce the product.

Getting to the economy, Chuck, I believe it was you who said something to the effect that perhaps early in the program, "to establish the confidence, you need to start even a development program or research program" – more specifically research – to start doing those in the area of quality, make sure you have got someone to manufacture the technology you are looking at. Don't wait until the project manager says, all right we are ready to buy, and then say, "My God, who have we got to make this thing now."

I think there is an area there we have really got to be sensitive to. In other words, you can do a lot in the R&D labs, but bring along the capability of a manufacturer to transfer or to infuse in that manufacturer the technology and development you need later.

BADCOCK: May I comment? First I would like to answer Irv's question. Yes. One of the things we have talked about here that needs to be pointed out, there needs to be a trade-off between fundamental understanding and testing. I bite my tongue here because I like the fundamental understanding. But, you can only trade that so far. People talk about, you know, if we understood everything, we would not have to test. I don't think that is true. Nobody is going to buy that.

So you have a region in the middle here with testing on one side and fundamental understanding and research on the other. You have a region in the middle where you can move these back and forth. So, I think, with NiCads, we are pretty much to the testing side at this point because we keep changing these things.

BLAGDON: The Galileo program is using a modular concept in its battery design power environments. That has already offered some system flexibility to the systems people, design flexibility that would not have been there had we selected or chosen a singular battery package for the thing.

I like the comments of the panel relative to the modular concept to power systems design. With respect to establishing a common data base industrywide, I think it has some definite advantages and has some system flexibility.

One other comment I would like to make is that the current Galileo program has been stretched out. That stretch-out gives us the opportunity to establish some real-time data that we did not have in the original program which, we believe, is going to lower the risk on the overall program.

So my comment basically is that time and sponsorship are also very, very critical in establishing this data base that we are looking for. You can accelerate test programs, but absolute confidence from an end user who does not necessarily fundamentally understand the system is only going to come with some real-time data.

But I would like to comment relative to the modular design concept, relative to establishing a common data base.

FORD: I would like to summarize. I think we have heard a large variety of inputs, all of which have to be taken collectively. And it may well be that we, in the technical field, have the same problem that you find in management by the mall distribution principle. That is, basically, you only have 20 percent of the information you need to make 80 percent of the decisions you have to make.

# LITHIUM CELL TECHNOLOGY AND SAFETY REPORT OF THE TRI-SERVICE LITHIUM SAFETY COMMITTEE

E. Reiss  
ERADCOM

What I would like to talk to you about today is the Tri-Service Lithium Safety Committee. This is a fairly small phase of a many-faceted problem that face all of us here.

This particular committee was initiated in September 1977 when representatives of the Army, the Navy, and the Air Force recognized that the lithium batteries are becoming the major military power source and that procedures should be established so that lithium batteries may be safely and responsibly employed.

(Figure 1-29)

This committee suggested that a tri-service group be established for the purpose of exchanging information on lithium batteries.

(Figure 1-30)

There is a fourfold purpose. The first was to exchange information on lithium batteries. Another area was to examine common areas of concern to the three services. The third was to provide guidance to the users. And the last was to set up common procedures where applicable, for the safe handling, deployment and disposal of lithium batteries.

(Figure 1-31)

Formally, this committee was organized in December 1977 as Lithium Battery Safety Group under the Joint Deputies for Laboratories Committee, Subpanel on Batteries and Fuel Cell Technologies.

(Figure 1-32)

Under a joint memorandum of agreement on batteries and fuel cell technologies, the Army is designated as the joint service focal point for lithium batteries and was appointed as the head of the safety group.

By July 1978, a charter for the group was officially accepted and extended to include NASA, the Department of Transportation, and other government agencies.

During the last 2 years, several key areas have been discussed at great length. These are shown on the figure, and I would like to expand upon each of these categories briefly for you and to tell you what conclusions we have been able to reach in a short period of time.

The first area is on transportation. When the committee was first initiated, we were talking about the first revision to the Department of Transportation Exemption No. 7052. Today we are looking at the seventh revision to Exemption 7052.

This safety group has been able to keep its members updated on each change, has been able to alert members when necessary, who need to be granted a party status to that exemption, as well as to our contractors.

And we have provided an opportunity for the members of the various services to meet with the Department of Transportation representatives to discuss the rationale and interpretation of those exemptions.

The second area of transportation concerns the FAA. One of our members, Paul Neumann, has been able to keep the services fully aware of the safety problems which have occurred in emergency locator transmitters.

The FAA has also been responsible for fostering and publishing an airworthiness directive and a technical specification order concerning lithium sulfur dioxide batteries for use in aircraft. Through this committee, the members have been fully aware of proceedings through the FAA.

The next area I would like to briefly touch on is disposal. Various reports, rumors, and opinions exist on the recommended methods for disposal of lithium batteries. This safety group has attempted to clarify within itself the issue of disposal. Success has only been marginal.

A major stumbling block of this committee is assessing the degree of hazard as defined by the EPA in their "Guidelines for Hazardous Waste Disposal" published in December 1978.

Adding to this problem is the multitude of chemistries, designs, manufacturers and users of lithium batteries. For example, there are at least 12 different chemistries of lithium cells in batteries.

One of these chemistries and designs was examined by Vasar, Inc., in Springfield, and they concluded that lithium sulfur dioxide cells of a balanced design did not contain significant concentrations of cyanide. In their report, this was so stated. An analysis of this report by the New Jersey Department of Environmental Protection concluded that sanitary landfills could be used for the disposal of balanced cells in batteries.

But, as I mentioned, there are at least a dozen different chemistries, and not all of the lithium sulfur dioxide chemistries have a balanced design.

As a committee, an Interim Guideline for Lithium Sulfur Dioxide Batteries was agreed upon to be followed until either firm clarification of the EPA Guidelines is established, or until specific testing against the EPA Guidelines establishes the degree of hazard. This is being looked at under an Army contract with LaPor, Inc., in Chevy Chase, Maryland.

(Figure 1-33)

The group's Interim Guidelines state that no more than 200 pounds of batteries shall be disposed of in a sanitary landfill per day.

Second, all disposal actions will be cleared with each state environmental protection agency. As I mentioned, the Vasar Report was looked at and evaluated by the State of New Jersey. Additional opinions may exist in various states throughout the country, and we felt it imperative that each state give their own opinion. What is good in New Jersey may not be good in California, or vice versa.

Next, cells, batteries will not be compacted or crushed or placed where they may be crushed.

And lastly, the landfill operators would be advised that cells contain lithium and acetonitrile, which are both possibly reactive and ignitable.

(Figure 1-34)

The next area I would like to talk about is storage. How shall we store lithium batteries, what shall we tell the users?

This question was asked at the first few meetings and discussed many times. Two aspects of storage became apparent: Should we protect the battery from the surroundings, or the surroundings from the battery? In part, as you know, the Department of Transportation Exemption 7052 describes packaging and materials and specific methods on sealing the batteries in plastic, cardboard, etc.

To further answer this question, though, several members of the safety group through their own agencies have begun studies and inquiries to assess this problem. The Army has determined that three depots have storage areas which will afford an acceptable level of safety. These are the Sharpe, Red River, and New Cumberland Army Depots. Characteristics of these areas are shown.

All the areas are to be well ventilated. Temperatures are to be less than 55°C. In effect, we are saying there that refrigerated storage is not necessary, but high temperatures must be avoided. The facilities may be either sprinkler protected or in noncombustible structures. Batteries should be segregated from other commodities, other flammables.

We have defined a 2000-square foot per pile stack limitation on batteries. We specified a minimum of two-foot clearance between the walls and any of the batteries. And lastly, since it is a flammable material, smoking is prohibited in the warehouse area.

Further, we have recommended that batteries should be disposed of as soon as possible after use and not returned to storage.

In the area of individual testing and test results, we found that this is the greatest area for data exchange. Programs from each Service have been updated at almost every meeting. It has happened that topics focused on lithium sulfur dioxide batteries and lithium thionyl chloride batteries in the three areas of experimental cells, service casting, and building reports.

This opportunity to share information in the area of lithium batteries, in particular safety, has resulted in several programs aimed at resolving common problems. One of these problems that will benefit the three Services, NASA, the FAA, and possibly industry, is the program I mentioned with LaPor.

In the area of battery design, thorough and complete discussions have existed. Proper and safe battery designs and acceptable procedures for using the batteries have been extremely important. Though, as you may have guessed, we all don't agree on any one design or any one chemistry, many commonalities have existed. These concerns have been incorporated into a NAVSEA Instruction No. 9310.1 issued in March 1979.

(Figure 1-35)

In addition to this, similar information can be obtained from the different Services or is being coordinated at this time.

*Key areas of design that we are looking for are that all cells shall have a case-to-cover seal continuously welded. This, in conjunction with the next point that the seal between the electrodes and the cover shall be glass or ceramic metal tight, should give us an hermetically sealed cell. For each particular cell we are recommending that a safety venting device be installed and incorporated into the design.*

The next point is that all metal parts of the cell or battery should be secured to prevent possible movement or shorting. In the area of battery design, we are recommending that each group of cells be connected in series with a fuse in series with a string of cells.

The next point is that whenever possible, completed battery assemblies should be procured from battery manufacturers. This is opposed to having cells sent out to an independent assembler who then constructs a battery in any configuration that he deems necessary.

In keeping with that, the last point is that assemblies should be by experienced – should not be by inexperienced personnel.

The last two points really go together. That we would prefer, whenever possible, to have the battery manufacturers who have the expertise, to actually construct the batteries.

In other areas covered by the NAVSEA Instructions, I mention them briefly here so that you are aware of them:

(Figure 1-36)

They pertain somewhat more to the Navy than the three Services. However, there are points that can be adhered to by the various users.

*Qualification Procedures and Documentation* – That is a major portion of the document, but it specifically talks about how the Navy will go to procure batteries. The same way with acquisition.

Under “Use,” they have a section which defines the proper means of selecting a battery, testing that should be done with the battery or cells to qualify that the battery is being used properly. Packaging, marketing, transportation, storage, and disposal are similar to the other comments that I have mentioned today.

I would like to conclude by stating that the important point of this group is that the various services and government agencies are developing a unified approach to deal with the design and use of lithium batteries. Each agency will still have its unique requirements, and exceptions will abound no matter what the committee can come up with.

Nonetheless, the frequent exchange of information of controversial or state-of-the-art issues provides a more meaningful data base from which future programs will be planned.

## DISCUSSION

OTZINGER: It looks like you are starting out in the right direction here. One of the things I noticed that was under “Design,” one of the problems they are having with lithium or one of the corrections to a problem with lithium, was not having positive limit in the design.

Now, you know the welded header is a step in the right direction. The seal takes care of the seal problem, and also terminals are ceramic or glass. I am surprised, was it an oversight or did you purposely not include positive limiting as a design feature?

REISS: It is not an oversight. The reason it was not considered in the specific guidelines is that many different applications may exist for the lithium batteries. There are some places, particularly in the Navy, where they are talking about sonobuoy applications where their safety criteria are considerably less than NASA or the Army might have.

Therefore, as an overall guideline, we would not recommend that all cells go to the ballast or lithium limited design if we are talking about sulfur dioxide. It is a topic that has been discussed frequently, and, when applicable, this is a general guidance. But, I excluded it from the NAVSEA Instructions. It is not covered in the NAVSEA Instructions, but it is being considered by the various services.

OTZINGER: My understanding is that you have pretty well solved your disposal problem by just simply discharging the cell all the way down.

REISS: In the lithium sulfur dioxide system, it eliminates the generation of cyanide, which is the key toxic point.

OTZINGER: My only other comment was, are these instructions going to be put out for people to comment on and to feed back to you any suggestions?

REISS: No. The NAVSEA Instructions is a public document. It is finalized. It can be updated, I would assume, as necessary. But it is not out for general comment with a known date for comment period.

BARNARD: You gave instructions for storage of batteries in bulk. Now, what happens when you have a lot of items with batteries inside them. What about storage of those, any particular problem?

REISS: I cannot comment specifically on sonobuoys. It has been my understanding that batteries are not normally stored in equipment, particularly in the Army. I have to speak from that background. There might be somebody here from the Navy.

BARNARD: Yes, they would be stored in sonobuoys.

REISS: I would assume the same general characteristics would exist. You would need well ventilated areas segregated from other combustibles, flammable materials.

BARNARD: One of the requirements for a sonobuoy is that it goes up to a temperature of 70°C. It cannot be stored in that temperature?

REISS: That would be unique then for the sonobuoys. What I have tried to do is give general guidelines that have come out from the committee. There are exceptions to every phase of this.

If we talk about the sonobuoys in particular, I just mention that they may not have a balanced chemistry, balanced cell design. That makes them unique. And because of that uniqueness, other considerations may have to be given to them.

For the Navy, you might try to get in contact with Tony Sliwa at Crystal City. He might be able to give you the more specific information on the Navy's viewpoint on the sonobuoys.

JOHNSON: My question relates to the NAVSEA instruction, particularly the safety venting instruction. Is the NAVSEA instruction oriented toward all lithium cells, or is it specifically for the sulfur dioxide system only?

REISS: No, it is a general statement for all lithium batteries, various chemistry designs.

JOHNSON: I see. Do you plan to have specific instructions for specific systems later on? In particular, the carbon monofluoride system? Will there be special instructions for the safety in that system?

REISS: As a committee, at this point we don't have any items on the agenda to answer that question directly. We will be addressing the chemistries in time, but at this point we don't have a specific item to look at just that from the safety viewpoint.

BADCOCK: Two comments: It is unusual to see water reactor things like thionyl chloride with lithium stored in a sprinkler protected room. You might want to comment on that. Why don't you call that a hermetic seal rather than just a continuous weld?

REISS: To answer your first question, the committee for the various Services have seen pieces of data which indicate that lithium batteries, lithium cells, are not an extreme hazard when exposed to water. In fact, we have, in the various Services, done experiments where we have extinguished lithium battery fires with water. Water does reduce the hazard.

What we are doing with the water, in effect, is lowering the temperature and reducing the cardboard or other packing material from burning. It lowers the whole hazard associated with the batteries. And you can put out lithium fires with water.

BADCOCK: But there are better fire extinguishing agents which probably should be used.

REISS: The better agent we have discussed in something called Lithex, which is a powder, a graphite-type powder. It does put out lithium. However, it is not readily available in all of the warehouse areas throughout the Services, at least.

We have found that water does prevent significant damage to the surroundings, and therefore, if there is a fire, we are willing to say a certain quantity of batteries is lost. We are not going to use them again electrically. If they burn, fine. The hazard is controlled to a small area, and we accept that risk.

SEITZ: You would not require a safety vent, for example, on a lithium iodide button cell, would you?

REISS: No, probably no.

TAYLOR: Just one question with regard to the design. I am wondering, should you, in fact, have some statement about heat dissipation? For example, if you get a battery, should your instructions include the fact that one should not pot it in solid potting material? That was missing from the NAVSEA specifications.

REISS: The NAVSEA Instructions actually have some wording in there about potting a battery. The specific wording I don't remember, but it states that potting may be used provided the vents are not obstructed.

As far as heat dissipation is concerned, it is not covered in the specific NAVSEA instructions. However, it has been discussed by the various Services and incorporated into some of the different designs. Some of the discussions we have had with battery manufacturers in particular for the specific applications.

It has not been ignored. But it is a general guideline. It is not complete as we may like to see.

TRI-SERVICE LITHIUM SAFETY COMMITTEE

INITIATED: SEPTEMBER, 1977

FORMALIZED: DECEMBER, 1977

Figure 1-29

LITHIUM BATTERIES SAFETY GROUP

JOINT DEPUTIES FOR LABORATORIES COMMITTEE  
SUB-PANEL ON BATTERIES AND FUEL CELL TECHNOLOGY

CHARTER ACCEPTED - JULY, 1978

Figure 1-31

PURPOSE OF LITHIUM SAFETY GROUP

EXCHANGE INFORMATION

EXAMINE COMMON AREAS OF CONCERN

PROVIDE GUIDANCE FOR USERS

SET-UP COMMON PROCEDURES

HANDLING, DEPLOYMENT, DISPOSAL

Figure 1-30

KEY TOPICS

- TRANSPORTATION
  - DOT EXEMPTION 7052
  - FAA
- DISPOSAL
- STORAGE
- INDIVIDUAL TESTING/TEST RESULTS
- BATTERY DESIGN - USAGE

Figure 1-32

## INTERIM DISPOSAL RECOMMENDATIONS FOR LITHIUM SULFUR DIOXIDE BATTERIES

1. NO MORE THAN 200 POUNDS PER DAY SHALL BE DISPOSED OF IN ANY SANITARY LANDFILL.
2. ALL DISPOSAL ACTIONS WILL BE CLEARED WITH EACH STATE ENVIRONMENTAL PROTECTION AGENCY
3. CELLS/BATTERIES WILL NOT BE COMPACTED OR CRUSHED OR PLACED WHERE THEY MAY BE.
4. LANDFILL OPERATORS WILL BE ADVISED THAT CELLS CONTAIN LITHIUM AND ACETONITRILE, BOTH POSSIBLY REACTIVE AND IGNITABLE.

Figure 1-33

## SUMMARY OF NAVSEA INSTRUCTIONS 9310.1

### DESIGN

ALL CELLS SHALL HAVE CELL CASE TO COVER SEAL CONTINUOUSLY WELDED.

THE SEAL BETWEEN ELECTRODE AND COVER SHALL BA A GLASS OR CERAMIC TO METAL TYPE.

EACH CELL SHALL HAVE A SAFETY VENTING DEVICE.

ALL METAL PARTS SHALL BE SECURED TO PREVENT MOVEMENT AND POSSIBLE SHORTING.

EACH GROUP OF CELLS CONNECTED IN SERIES SHALL CONTAIN A FUSE.

WHENEVER POSSIBLE COMPLETED BATTERY ASSEMBLIES SHOULD BE PROCURED FROM A BATTERY MANUFACTURER.

ASSEMBLY BY INEXPERIENCED PERSONNEL SHOULD BE AVOIDED.

Figure 1-35

## STORAGE FACILITIES

- WELL VENTILATED
- TEMPERATURES LESS THAN 130°F (55°C)
- SPRINKLER-PROTECTED OR NONCOMBUSTIBLE STRUCTURE
- SEGREGATED FROM OTHER COMMODITIES
- LIMITED TO 2000 SQUARE FEET PER PILE/STACK
- A MINIMUM OF 2 FEET CLEARANCE BETWEEN ANY WALL AND BATTERIES
- SMOKING PROHIBITED

Figure 1-34

## OTHER AREAS COVERED IN NAVSEA INSTRUCTIONS 9310.1

- QUALIFICATION PROCEDURES, DOCUMENTATION
- ACQUISITION
- USE
- PACKAGING, MARKING
- TRANSPORTATION
- STORAGE
- DISPOSAL

Figure 1-36



## NASA/MARSHALL'S LITHIUM BATTERY APPLICATIONS

E. Paschal  
NASA/MSFC

(Figure 1-37)

This first chart consists of items I will cover in my presentation today. I gave you a presentation about 2 years ago on the NASA/Marshall battery applications, different battery applications. Today I am going to expand a little bit on what I gave previously.

The items will be a brief summary of the applications, general battery description, and in particular, I will discuss a particular battery, the IECM battery, design and construction details, thermal vacuum test, projection tests, and acceptance tests.

(Figure 1-38)

The second chart lists the various program applications. In most cases, these batteries are being flown on the SRB, an external tank. In particular, the SRB has one range safety battery. The external tank has two range safety batteries. So, there are four on each flight.

Also, in the SRB on the frustum, there are two frustum location "A" batteries. The IECM experiment will fly in Earth orbit, the same for the TCSE. IECM formation has induced environmental contamination monitors.

TCSE is an experiment thermal controlled services. Generally, all these batteries are lithium carbon monofluoride types rated 18 ampere-hours and have 13 cells in each housing.

In all cases, with the exception of the IECM battery, a NylaFil composition of fiberglass and nylon housing is utilized. Aluminum housing is used for the IECM batteries. All qualification tests each of these batteries have been completed.

(Figure 1-39)

Turning specifically to the IECM battery, I have shown a top view of the battery, looking down from the top. You will note that the cells are viewed looking down from horizontal. On the far end up there is an open cavity of space there, and the vents are facing in that direction.

There is a safety protection on the end of the vents to keep anything out of it. This area in here is what I am referring to as being an open area. And on this end we have it vented, as you will see later on another figure there, just where that vent is.

Between each of these rows is an aluminum fan that comes up through here and that way. This one here comes down, up this way here. That is welded to this side and to this side.

Down here is a thermostat.

(Figure 1-40)

This one shows the battery looking from the side. As you see, the cells are stacked on top of each other. This area here is the void area I mentioned. Here is a fuse and here is a connector.

This is a pressurizing valve and cover seal.

(Figure 1-41)

This is a view looking at the end. Here is the crosshatch. You will see that the aluminum fans are designed to carry the heat to the outside housing. These fans come down and are welded to the base of the battery. The cells are against the aluminum fan. They also have an insulated thermal trip over the cells and over the wire there to protect them.

There again you see the fuse, the connector on this end here. This part in here is the relief part, right in here. That is a protection cover over there to keep anything from getting into it.

From this lower point back, all of this area is potted with a wax to aid in thermal control.

(Figure 1-42)

Here is a simplified schematic of the battery. As you see, there is the fuse. Seeing these with the cells and a thermostat there protect against all the temperatures.

Also, there are two thermistors used in this experiment. These thermistors are routed to the experiment electronics package. At the present time, they are not utilized to turn off the experiment, but they could be turned off. This thermostat is set to open at  $175 \pm 5^\circ \text{ F}$ .

(Figure 1-43)

On this chart I have listed some of the thermal vacuum tests that we have drawn on the battery. There are two series of tests. Certain ones are going to be done at the plant and others are done at Marshall on full battery.

In addition to the thermal vacuum test, of course, we are going to chart vibration tests. These tests are basically the same. There is a little difference in the test. For example, on the vendor test the vacuum is  $1 \times 10^{-4}$  torr. On the Marshall test it is  $1 \times 10^{-6}$ .

The side temperatures are slightly different; the cold plates are slightly different. The load currents that we run are slightly different.

You will note that in each case, it started out as a higher current and dropped off. The higher current is used for 5 to 15 minutes, 15 minutes over there and 5 minutes here, and has dropped down. Using it at the lower test, it will run 3 to 4 hours apiece.

A single battery goes through a cold test and a high-temperature test. As I pointed out, the thermostat is designed to open at  $175 \pm 5^\circ\text{F}$ , so  $180^\circ\text{F}$  is maximum.

(Figure 1-44)

As part of the acceptance test on the batteries, there is a cell block test which is used to measure capacity, using a cell out of a particular block from which the battery is from. The minimum is 18 ampere-hours.

There is a cell impedance test performed, also a dielectric strength insulation and resistance test, thermistor test, pin case voltage test, dimensional check, battery seal, and battery case seal. This consists of pressurizing the housing to 12 psig and holding that. The case should hold that pressure for 5 minutes without a drop in pressure in tests of 0.1 psig.

The final battery case seal consists of putting the battery in  $160^\circ\text{F}$  thermal vacuum chamber for 4 hours. There is to be no wax leak when the battery is turned on its side.

At Marshall, an outgas and leak test was also performed on the battery. This test is  $158^\circ\text{F}$ , 48 hours at  $1 \times 10^{-6}$  torr. There is no wax leak within outgas specifications.

From the typical data that we picked up on some of our test batteries, the seals number 7, 8, 9, and 10, the cell block tests range from about 20 to about 23 1/2. The voltage was a little higher at the beginning of the test. At the  $158$  to  $160^\circ\text{F}$  temperature following this test, there is a matter of open circuit voltage.

(Figure 1-45)

Following all of these individual battery evaluation tests, we performed several systems tests in which the batteries were installed on an actual flight IECM package and were installed in the thermal vacuum. They are old batteries on the IECM, and they all figured through the isolating valve to a common bus.

The test setup was such that the systems had capability of running some items from ground power with the battery turned off. One of our batteries saw something like 15 cycles ranging from 0 to  $70^\circ\text{C}$ , estimated 300 to 400 hours under  $70^\circ\text{C}$ . There was a hold somewhere on the order of 10 to 24 hours. In some cases that elevator jumped.

On the first systems test, the total output recorded was 42 ampere-hours. With four batteries on board, the total capacity was 72 ampere-hours.

It was somewhat surprising that the capacity was so low. But, in going back and looking at the records, it was determined that there were some periods of time when they were performing ground tests or ground trials, the batteries were actually on low.

So, we probably don't know exactly what the total capacity was on a good many batteries. It was supposed to have been off. We know it was much higher than the 42 ampere-hours. That is just what was observed. So when the batteries are turned off now, they are off.

The second test was done a little later and was still in the same category 0 to 70°C. The capacity was 66.43 ampere-hours, about 10-percent total capacity there. We expected to get some reduction in capacity due to the high temperature and the higher discharge rate. So that was considered and checked for.

The system itself, maximum experiment, uses something like about 55 ampere-hours.

In each of these tests, two of the batteries were discharged completely. Those two that discharged did vent. There was no indication or institution of any high temperature. No knowledge of this venting was revealed until the batteries were removed from the system and the cover was removed.

The other two batteries on each of the two systems had residual capacities left in them. There was no cell venting in the case of either of the two batteries with residual capacity.

We have yet to evaluate the amount of capacities left on the systems test.

## DISCUSSION

HESS: Two questions: What were the discharge rates on these systems tests?

PASCHAL: Systems tests with about 0.8 of an ampere-hour per battery.

HESS: What were the stoichiometric proportions of the lithium?

PASCHAL: I can't answer that. I don't have that figure with me.

BENNETT: Can you tell me what the weight of the battery system was?

PASCHAL: About 12-1/2 to 13 pounds.

It was caused to be a little heavy. It was necessary to put wax in it in order to get the long, 3- to 4-hour usage.

GROSS: Several questions. First, the cells did vent under full discharge? I presume this is unacceptable. Is this correct?

PASCHAL: The two that were discharged on the systems test did vent.

GROSS: Yes. My question is, do you consider this unacceptable and therefore you will do something in the program to correct the design so that won't happen in the future? Or, do you consider this satisfactory?

PASCHAL: At this particular point in time we do not contemplate doing anything.

The reason we don't is that this venting occurred at what appeared to be without any generation of heat at a point when the batteries were pretty well impinging. It was not known that it did not vent gas out of the battery housing. So, there was no contamination.

Incidentally, this experiment is an IECM, Inducement Environmental Contamination Monitoring, and it is extremely important that we not vent outside the housing. Actually, the housing will vent at about 52 psig.

GROSS: My second question was regarding voltage.

When you operate over a large temperature range of approximately 170 or 180°F down to 32 degrees, as I understand the ranges from the chart, there would be a very large voltage change just due to the very thermodynamic behavior of the system. And second, this is, of course, aggravated by a range of discharge currents.

So, my question is, what voltage range did you experience on the system, and, secondly, what if anything was done in the design to minimize the voltage?

PASCHAL: The voltage was between 26 and 32 volts, which were the requirements set up on the system. I haven't looked at all of the data, but as far as I can recall, they are all within the range of 26 to 32 volts. The colder temperatures results in colder voltage there until you got real high. Temperatures on the battery started coming free, and then, of course, the voltage dropped. The systems tests terminated around 26 volts.

GROSS: That is one of the important problems with this system in a lot of applications. And it is worth looking at closely.

OTZINGER: Last year, during the lithium session, we had people from NASA Headquarters, discussing safety requirements. One of the things they pointed out was that for vehicles leaving KSC — and I believe this being shuttle as well — the design will have to be submitted to the safety group at KSC for their approval.

Has this been done and has this battery been approved for flight?

PASCHAL: We have received several preliminary approvals of the system. Final approval has not been given at this time. We are in the process of discussing it with JSC. Most likely, we will want to run some supplemental tests over what we have done. But, to answer your question, it has been submitted to JSC. Final approval has not been received.

HALPERT: Is there a lot qualification? In other words, have you put separate ones aside that are going to fly, or are they going to fly new ones all over again?

PASCHAL: There is a qualification for the batteries, particular battery design. We have qualified a certain number of batteries for the design of the system. Then, of course, we run through the check, including the precase venting test and the high-temperature thermal vacuum at both Marshall and at the vendor's plant. All of that constitutes an acceptance of each specific battery.

HALPERT: But you are going to buy a new lot for the actual mission?

PASCHAL: Well, yes. There is a new lot for each — for several batteries. This group that I showed you had several lots involved.

ORGANIZATION: EC12	MARSHALL SPACE FLIGHT CENTER MSFC LITHIUM BATTERY APPLICATIONS	NAME I. E. PASCHAL DATE NOVEMBER 1979
<p>1. SUMMARY OF MSFC APPLICATIONS</p> <p>2. GENERAL BATTERY DESCRIPTION</p> <p>3. IECM BATTERY</p> <ul style="list-style-type: none"> <li>o DESIGN &amp; CONSTRUCTION DETAILS</li> <li>o THERMAL VACUUM TESTS</li> <li>o BATTERY ACCEPTANCE TESTS</li> <li>o SYSTEMS TESTS</li> </ul>		

Figure 1-37

ORGANIZATION: EC12	MARSHALL SPACE FLIGHT CENTER MSFC LITHIUM BATTERY APPLICATIONS	NAME I. E. PASCHAL DATE NOVEMBER 1979												
<p><u>SUMMARY OF MSFC APPLICATIONS</u></p> <table border="0"> <thead> <tr> <th><u>PROGRAM</u></th> <th><u>FUNCTION</u></th> </tr> </thead> <tbody> <tr> <td>SRB</td> <td>FRUSTIUM LOCATION AIDS (FLA)</td> </tr> <tr> <td>SRB</td> <td>RANGE SAFETY</td> </tr> <tr> <td>ET</td> <td>RANGE SAFETY</td> </tr> <tr> <td>IECM</td> <td>PAYLOAD EXPERIMENT POWER</td> </tr> <tr> <td>TCSE</td> <td>PAYLOAD EXPERIMENT POWER</td> </tr> </tbody> </table> <p><u>GENERAL BATTERY DESCRIPTION</u> - ALL APPLICATIONS</p> <p>BATTERY TYPE: 13 - 18 AH LI/CF CELLS</p> <p>VENDOR: EAGLE PICHER</p> <p>HOUSINGS:</p> <p>FLA, RSS, TCSE: G4/45 NYLAFIL</p> <p>IECM: ALUMINUM</p> <p>QUALIFICATION STATUS: COMPLETE</p>			<u>PROGRAM</u>	<u>FUNCTION</u>	SRB	FRUSTIUM LOCATION AIDS (FLA)	SRB	RANGE SAFETY	ET	RANGE SAFETY	IECM	PAYLOAD EXPERIMENT POWER	TCSE	PAYLOAD EXPERIMENT POWER
<u>PROGRAM</u>	<u>FUNCTION</u>													
SRB	FRUSTIUM LOCATION AIDS (FLA)													
SRB	RANGE SAFETY													
ET	RANGE SAFETY													
IECM	PAYLOAD EXPERIMENT POWER													
TCSE	PAYLOAD EXPERIMENT POWER													

Figure 1-38

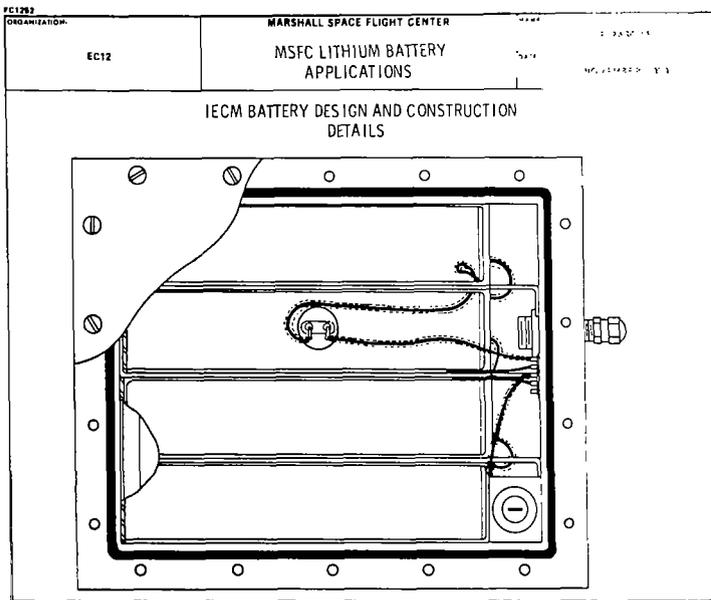


Figure 1-39

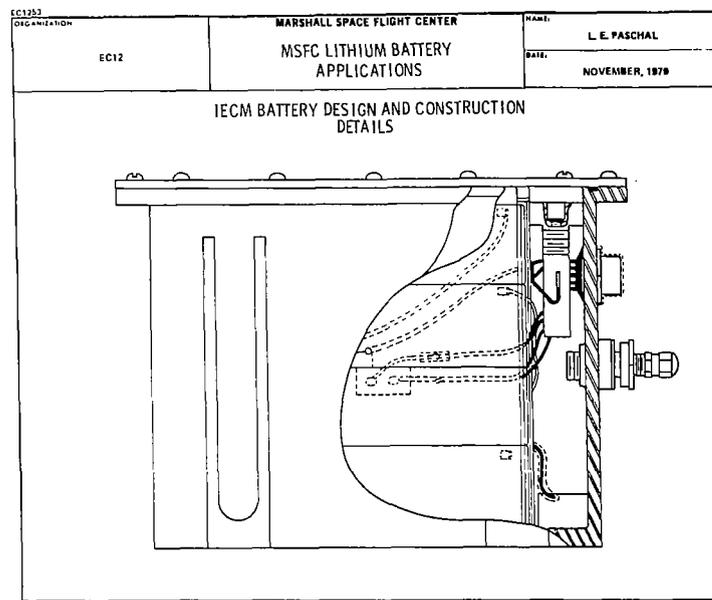


Figure 1-40

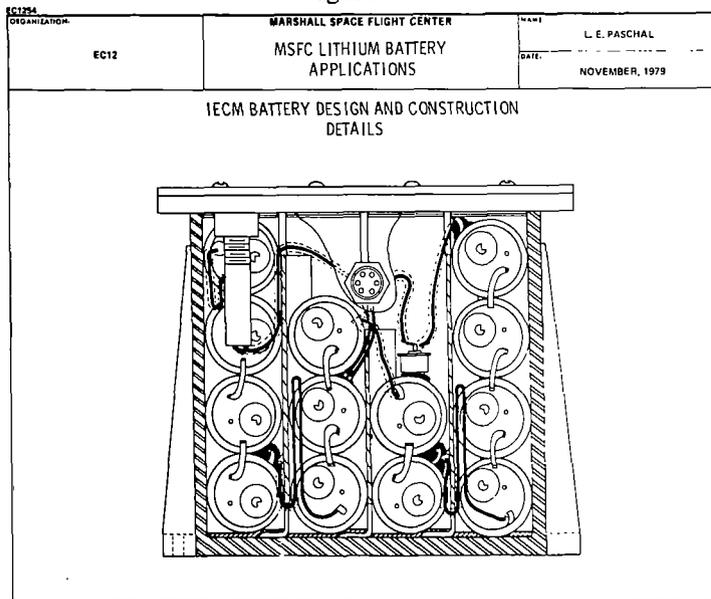


Figure 1-41

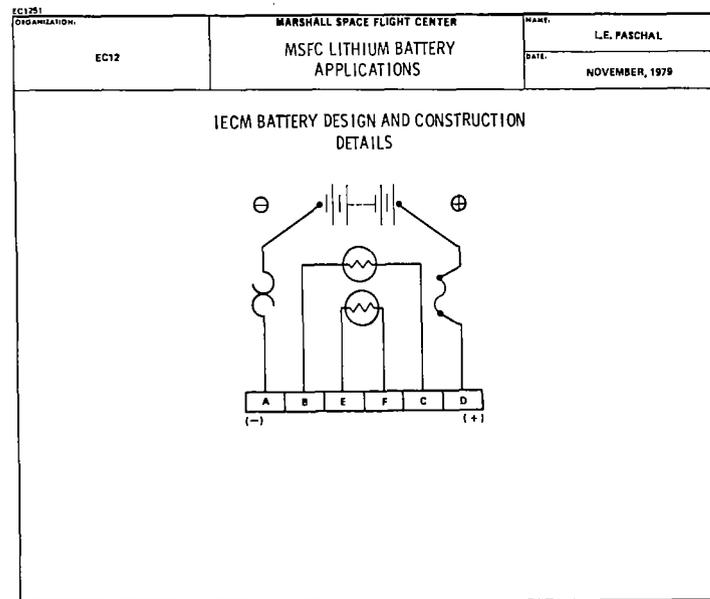


Figure 1-42

ORGANIZATION: EC12	MARSHALL SPACE FLIGHT CENTER MSFC LITHIUM BATTERY APPLICATIONS	NAME: L. E. PASCHAL DATE: NOVEMBER 1979
<u>THERMAL VACUUM TESTS</u>		
<u>VENDOR TESTS</u>		<u>MSFC TESTS</u>
1 X 10 <sup>-4</sup> TORR SHROUD -300°F MOUNTING: CELL HORIZONTAL		1 X 10 <sup>-6</sup> TORR MOUNTING: CELL HORIZONTAL & VERTICAL
<u>COLD TEMP. - COLD PLATE</u> 32° +5°F -0		<u>COLD TEMP. - COLD PLATE</u> 20°F ±5°F
2.3 AMPS - 5 MIN. 1.6 AMPS - 4 HRS. - 50 MIN. 1.5 AMPS - 1 HR.		1.72 AMPS - 15 MIN. 1.3 AMPS - 1 HR. - 45 MIN. 1.2 AMPS - 3 HRS.
AMBIENT TEMP. & PRESSURE 1.4 AMPS - 1 HR.		
<u>HIGH TEMP. - COLD PLATE</u> 100° +0°F -5		<u>HIGH TEMP. - COLD PLATE</u> 104°F ± 2°F
2.3 AMPS - 5 MIN. 1.6 AMPS - 4 HRS. - 50 MIN. 1.5 AMPS - 1 HR.		1.2 AMPS - 1 HR. 1.72 AMPS - 15 MIN. 1.3 AMPS - 1 HR. - 45 MIN. 1.2 AMPS - 3 HRS.
AMBIENT TEMP. & PRESSURE 1.4 AMPS - 1 HR.		AMBIENT TEMP. 1.2 AMPS - 1 HR.
MAX. BATTERY TEMP. 180°F		

Figure 1-43

ORGANIZATION: EC12	MARSHALL SPACE FLIGHT CENTER MSFC LITHIUM BATTERY APPLICATIONS	NAME: L. E. PASCHAL DATE: NOVEMBER 1979		
<u>ACCEPTANCE TESTS</u>				
CELL BLOCK CAPACITY		>18 AH		
CELL IMPEDANCE		<1.0 OHMS		
DIELECTRIC STRENGTH (500 V, 60 HZ/60 SEC)		<.5 MA		
INSULATION RESISTANCE (100 V DC/2 MIN)		>50 MEGOHMS		
THERMISTOR TESTS		PER CALIB. CURVE		
PIN/CASE VOLTAGE TEST		<250 MV		
DIMENSIONS		PER DRAWINGS		
BATTERY CASE SEAL PRELIM. (12 PSIG)		<.1 PSIG DROP/5 MIN		
FINAL BATTERY CASE SEAL (160°F/4 HRS; 1 X 10 <sup>-4</sup> TORR)		NO WAX LEAK		
MSFC OUTGAS/LEAK TEST (158°F/48 HRS; 1 X 10 <sup>-6</sup> TORR)		NO WAX LEAK; WITHIN OUTGAS SPECS.		
VENDOR/MSFC DATA:				
SERIAL NO.	7	8	9	10
CELL BLOCK AH	23/23.5	21.5	21.25/21.5	20.0/20.5
VOLTAGE PRE-OUTGAS	39.0	39.1	38.1	38.3
VOLTAGE POST-OUTGAS	38.2	38.3	37.3	37.2

Figure 1-44

ORGANIZATION:  EC12	<b>MARSHALL SPACE FLIGHT CENTER</b>  MSFC LITHIUM BATTERY APPLICATIONS	NAME: L. E. PASCHAL
		DATE: NOVEMBER 1979

SYSTEMS TESTS

○ THERMAL VACUUM

- PART OF FULL IECM TEST
- 1 X 10<sup>-6</sup> TORR
- 4 BATTERIES (72 AH TOTAL CAPACITY) ON BUS
- 15 TEMPERATURE CYCLES 0 - 70°C (ESTIMATED 300/400 HRS. UNDER 70°C)
- HOLDING 10 - 24 HOURS

○ TEST 1 RESULTS

- KNOWN DISCHARGE CAPACITY 42.0 AH (20/21 AH AT 70°C)
- UNKNOWN DISCHARGE CAPACITY DUE TO INSTRUMENTATION PROBLEM
- TWO BATTERIES DISCHARGED - CELL VENTING
- RESIDUAL CAPACITY TWO OTHER BATTERIES - NO CELL VENTING

○ TEST 2 RESULTS

- KNOWN CAPACITY DISCHARGE 66.43 AH
- TWO BATTERIES DISCHARGED - CELL VENTING
- TWO BATTERIES - RESIDUAL CAPACITY - NO CELL VENTING

SESSION II

LITHIUM CELL TECHNOLOGY AND SAFETY

G. Halpert, Chairman  
Goddard Space Flight Center



## HIGH ENERGY DENSITY BATTERY DEVELOPMENT STATUS REPORT

A. Willis  
NOSC

(Figure 2-1)

Looking at the Navy applications for high energy density batteries, you can see quite a range of applications, rates, and capacities; anywhere from remote sensors with the low rate, low capacity to the vehicular propulsion, which is high rates and high capacities.

(Figure 2-2)

As a net result, we have been looking or have developed a family. The largest one is a low-rate undersea implementation type of battery. Then, you see the 120-kilowatt-hour high rate for undersea propulsion. We have the 1.2-kW high rate battery for economeasures equivalent 600-watt-hour medium rate battery for a manpack for the Marine Corps.

In the middle of the illustration there are various cell technologies including the prismatic, the D sizes, and other assortment of button assortments and discs.

The film I have is what we did almost a year ago in the development, testing the first developmental cells of a large 17-inch thionyl chloride cells.

May I have the film, please?

(Film)

I defy any of the other cells you have to come through this test equally well. The interesting thing, the cell that went bad in reverse voltage gave this characteristic.

(Figure 2-3)

The important thing, of course, is this point right here. We have done a considerable amount of investigation, and we find that there is a critical point here in the neighborhood of -0.9 volts. Every cell that has ruptured in reverse voltage has gone to this point just prior to rupture.

So, it is important if you don't have an internal means of protecting or preventing that voltage appearing in the reverse direction on any of the lithium cells, you should have a Shockley diode to parallel it and prevent that voltage.

(Figure 2-4)

As a result of this test which was a 500-ampere hour, 17-inch cell, we decided on an improvement effort to obtain full capacity which means from 1/2- to 1-3/8-inch thick cell, from 500 ampere-hours to 1500 ampere-hours ambient temperature.

Obviously, we needed some work done on the vent relief device. We need a higher current feedthrough. And we had to improve the reverse voltage technique and to reduce the case weight.

(Figure 2-5)

A review of the safety problems indicates that three things can occur. Explosion occurs when the lithium melts, and the resolution of this, of course, is to prevent the lithium from melting. Release reactive materials from the cell before the lithium melts or control the lithium when it melts.

Explosion can occur when the cells are deeply discharged, and you have to provide some electrical controls either internally or externally to prevent voltage reversal. Hazardous materials are expelled from the cells during adverse conditions. We can contain, dilute, or minimize the quantity of hazardous materials and increase the tolerance for adverse conditions.

(Figure 2-6)

We said we were going to do some additional tests in the fall of 1978. Well, this is fall of 1979, so 1 year later and \$1 million later we now have a new set of cells.

This is a typical and desirable set of curve that we are looking for. This particular curve was on one of the smaller cells, a 2 1/2-inch diameter cell performing at 0°C.

Thus, you will notice here that we started the open circuit voltage, and it drops down to the 3 volts, a fairly high rate. That is a 2-ampere rate on the 5-ampere hour cell. Now down to about 3 volts, it stays here and falls off rapidly. Passes through 0 to about -0.1 at which time it locks up an internal switching device and holds it constant for as long as you want to go.

Interesting, we took temperature at the same time and the normal heating during discharge, as it came to the point where there is no more lithium, the internal resistance went up. And being a constant current drive, the temperature was increased until the lockup took place, and then the normal cooling curve resulted.

(Figure 2-7)

We had four more cells of the large configuration just this month – let's see, about the latter of September. This is a 17-inch cell under the same conditions of 12-ampere rate at 0°C. Again, it gave pretty near the flat configuration we have looking at this curve in here as to why that dropped off.

It fell off rapidly at a predetermined time. It dropped momentarily to the last – the neighborhood to 0.1 to 0.3, then locked up and stayed constant for the rest of its life. This is about 150 to 180 percent of the ampere-hour rating of this cell, and that is a safe discharge reverse voltage condition.

(Figure 2-8)

We are now really looking at the future, and we see a sort of family of applications or a family of cells. This should meet most of our applications ranging from low rate, medium rate, high rate, and the very high rate which is usually the reserve cell, the small, medium, and large capacity. This is sort of a family of cells that we think are immediate to the Navy applications.

#### DISCUSSION

OTZINGER: Will you describe how you achieve lockup?

WILLIS: This is essentially proprietary information with ALTUS.

OTZINGER: I see.

LEAR: When you did the discharges after storage or whatever, did you notice any of the lag in the voltage coming up through the potential?

WILLIS: Every cell that we discharge we do a depolarization curve to measure that time element, and the most severe that we have seen has been 12 seconds between the time the load was up high and the voltage was up above 3 volts. Normally it is in the order of 1 second.

LEAR: I have one other question. These were 150-, 120-ampere hour cells?

WILLIS: 1500-ampere hour cells.

LEAR: Why did you go so long in reverse direction with the voltage continuing on?

WILLIS: When a cell is in a battery configuration, it can see 100-percent ampere-hour capacity.

Assuming a cell is dead due to long period of storage and internal leakage of some sort, when you put the battery in service, the maximum it will be able to see is 100-percent rated capacity.

We take it into 150, maybe 200 percent just as a safety factor, just to prove that the thing is not really working.

ANGRES: Have you had any accidents lately with cells in reversal? And question number two is, is there any significant physical data of the reproducible Altus technology? I have not seen anything.

WILLIS: As I said, we received four more of the experimental cells in the larger configuration at 1500 ampere-hours. We put all four of them on discharge and reverse voltage. One did rupture, but it was predictable.

(Figure 2-9)

In the early physical measurements of the cell, which is cell No. 94 there, you can see it was lightweight, about half a pound lightweight. And then we put that one on discharge and reverse voltage with this result.

(Figure 2-10)

You will notice that there was number one, a discontinuity during the discharge which, again, flagged that one as a bad cell, I will say. Went down into reverse voltage and got very erratic here.

Not it lasted in excess of 150 percent of its capacity. But in order to obtain data as to what causes reversals – I mean explosions – and how long it would go before it would happen, we let the thing continue. And again, as soon as we hit -0.9 volts, it went.

So, it was predictable. We watched it, we knew it was going to happen, and that is it.

LEAR: Is the discharge rate the same after you go into reversal?

WILLIS: It is 12 amperes constant current.

LEAR: Totally? In other words, you took out more than 2400-ampere hours capacity out of that cell?

WILLIS: Yes. Well, we did not take it out. It was driven at 12 amperes. After reversal it is driven at 12 amperes.

LEAR: You took out roughly 1100 ampere-hours of capacity, 96 hours.

WILLIS: Say this was the cutoff point . . .

LEAR: 95 hours. About 1100 ampere-hours of that cell.

WILLIS: *Actually to the cutoff point. Now I don't have the discharge capacity there.*

(Figure 2-11)

This is the setup we used in which we take a power supply and actually drive it at a constant controlled 12 amperes during the whole cycle. It is 12 amperes because this particular cell is rated at 1200 ampere-hours at 0°C. 1500 ampere-hours at ambient temperature.

BENNETT: Have you got any shelf-life data on these at all at any temperature conditions? Have you noticed any ceramic seal problems or GTM problems?

WILLIS: We do not have any shelf-life data on the large cells. It is the same ceramic that is used in small cells. We have had them around for a maximum of 2 years with no deterioration whatsoever as far as the seals are concerned.

BENNETT: Can you tell me what orientation they were in?

WILLIS: Usually they are just horizontal, flat.

BENNETT: With the seal upright?

WILLIS: With the seal upright.

BENNETT: Have you ever done any inverted?

WILLIS: Not specifically.

SLIWA: Have you prepared any, or are you preparing any information on the safe way in which you dispose of these batteries once they are developed? Also, what would be the storage requirements?

WILLIS: On storage, the primary purpose, of course, is to prevent short circuit. It is to protect the terminal.

Secondly, this particular chemistry, as I understand it, is damaged with continued storage in excess of 130°F. As far as disposal is concerned, we find that they dispose very readily at sea.

We have done experiments by submerging the cells in salt water in barrels where we can observe it. In answer to this morning's question about using water to extinguish fires in relationship to the unit, apparently what happens is that the water will percolate or go into whatever opening is on the cell. In our case, it actually generated its own opening through electrolytic action on the case, and then it percolates. A little water goes in, and as soon as it hits the lithium or whatever elements are inside, it generates a gas and blows the water back out again. A little water goes in and then percolates back out, and it keeps that up over a long period of time.

And at no time is there any thermal runaway or major reaction. So, at sea disposal, seems a very convenient way for us, anyhow.

SLIWA: For shore disposal we would still have to consider this hazardous waste, just as the Navy considers all lithium sulfur dioxide, and any other lithium battery is considered hazardous waste under any conditions.

WILLIS: Not really. They are not a pressure vessel. If they had been discharged all the way down, there would be little or no toxic material in it and no pressure in it. So, while I would recommend handling them with reasonable amount of care, I see no reason why they cannot be disposed of as industrial waste.

SLIWA: We will have to pass this through the EPA.

WILLIS: Yes.

There is no toxic materials in the sense that it is injurious to the health, long leaching problems, or anything like that. No sign of that.

SLIWA: Concerning your tests, do you expect to continually add more tests as your test series goes on? Or, do you feel that the tests that you are now conducting will be complete life-cycle type testing that is required?

WILLIS: We have to obviously test more cells to get a statistical base. We are going on to additional testing using multiple cells in a battery configuration. The first one will be a three-celled battery configuration which is scheduled to go on at Wiley Laboratories.

(Figure 2-12)

This is the sort of matrix that we normally use; discharge rates at primarily 0°C, which is our underwater application. Then, we have vibration and shock, trying to get statistical information on reverse voltage and some of the hazard evaluation. And the last three cells on this test have a battery configuration.

SLIWA: How does this compare with the technical standard that we have to have and some other test requirements?

WILLIS: I think although it does not address specific shipping containers and things like that, it does take us far in excess of anything they are requesting. Our vibration and shock, for instance, is far in excess of any of those specific applications I have seen.

Dry battery specification Mil B-18 takes the low frequency and high frequency vibrations. It also takes the drop, as you saw it, of 250 gs.

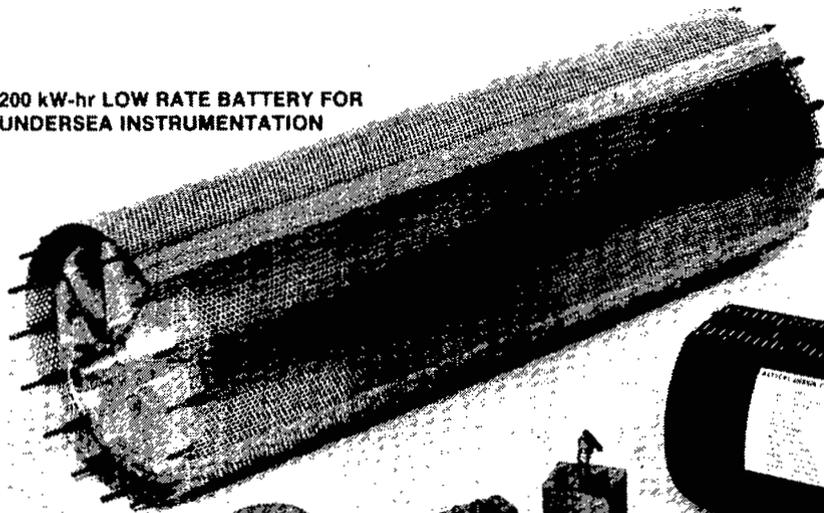
# NAVAL APPLICATIONS OF HIGH ENERGY DENSITY BATTERIES

Rate \ Size	Small (~ 10 AH)	Medium (~ 100 AH)	Large (~ 1000 AH)
Low (100 hr)	Experimental Equipment Remote sensors		Remote sensors Mines Aids to navigation Standby power
Medium (10 hr)			Submersibles
High (1 hr)	Sonobuoys, Portable communications	Countermeasures Decoys	
Very high, reserve (0.1 hr)	Missiles Countermeasures	Torpedoes Targets	

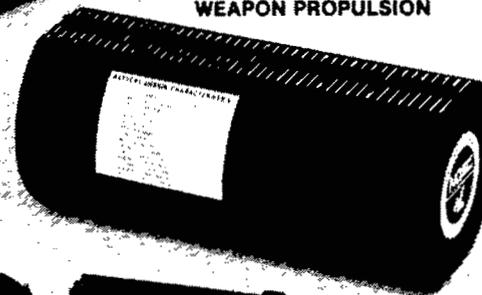
Figure 2-1

**NOSCO** LITHIUM THIONYL CHLORIDE BATTERY  
DEVELOPMENT PROGRAMS

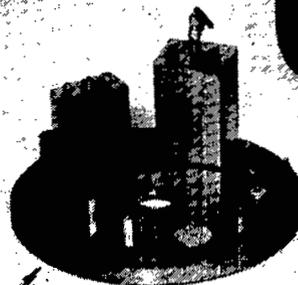
200 kW-hr LOW RATE BATTERY FOR  
UNDERSEA INSTRUMENTATION



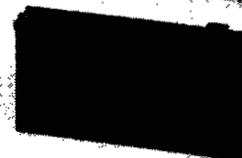
120 kW VERY HIGH RATE  
BATTERY FOR UNDERSEA  
WEAPON PROPULSION



1.2 kW-hr  
HIGH RATE  
BATTERY FOR  
ELECTRONIC  
COUNTERMEASURES



LISOCI<sub>2</sub> CELL TECHNOLOGIES



600 W-hr MEDIUM RATE BATTERY  
PACK FOR FIELD TRANSCEIVER

Figure 2-2

# TEST CELL DISCHARGE/REVERSE VOLTAGE PROFILE (OVERALL)

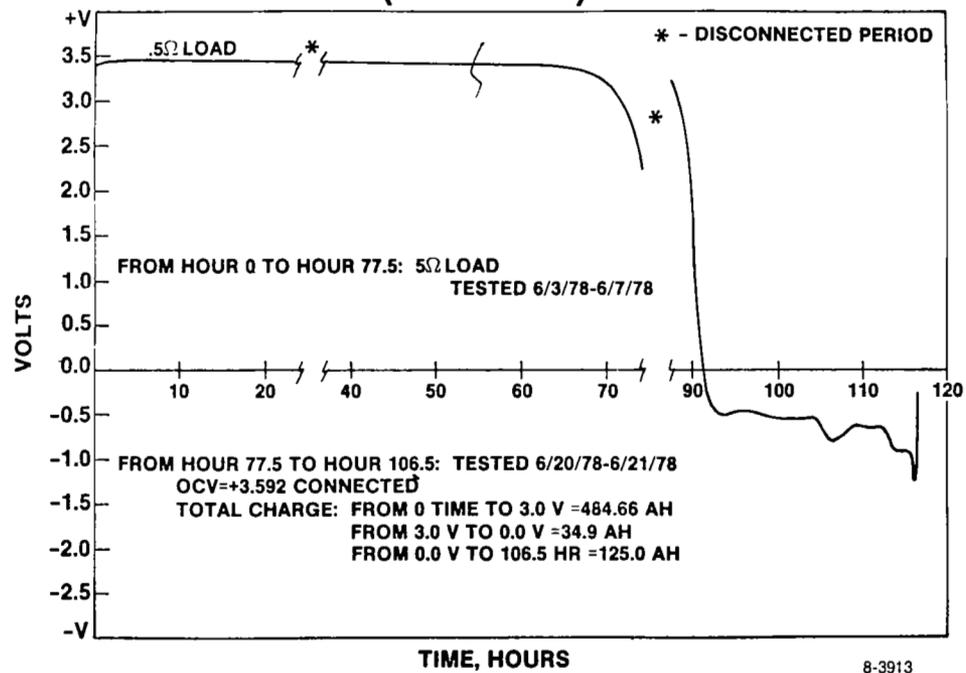


Figure 2-3

# HEDB PROGRAM CELL IMPROVEMENT EFFORTS

1. Obtain full capacity
2. Develop reliable pressure relief vents
3. Develop high current electrical feed-through
4. Develop anti-reverse voltage technique
5. Reduce case weight

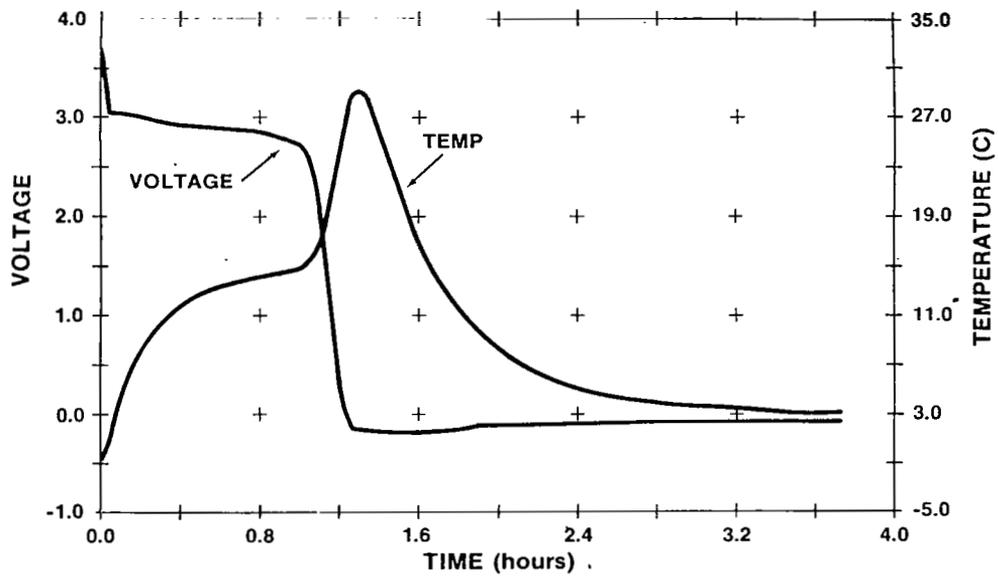
Figure 2-4

## SAFETY SITUATION

PROBLEM	SOLUTION
● Explosions occur when lithium melts	● Prevent lithium from melting ● Release reactive materials from cell before lithium melts ● Control the lithium when it melts
● Explosions occur when cells are deeply discharged	● Provide electrical controls to prevent voltage reversal
● Hazardous materials are expelled from cells during adverse conditions	● Contain or dilute expelled products ● Minimize quantity of hazardous materials ● Increase the tolerance of cells to adverse conditions

Figure 2-5

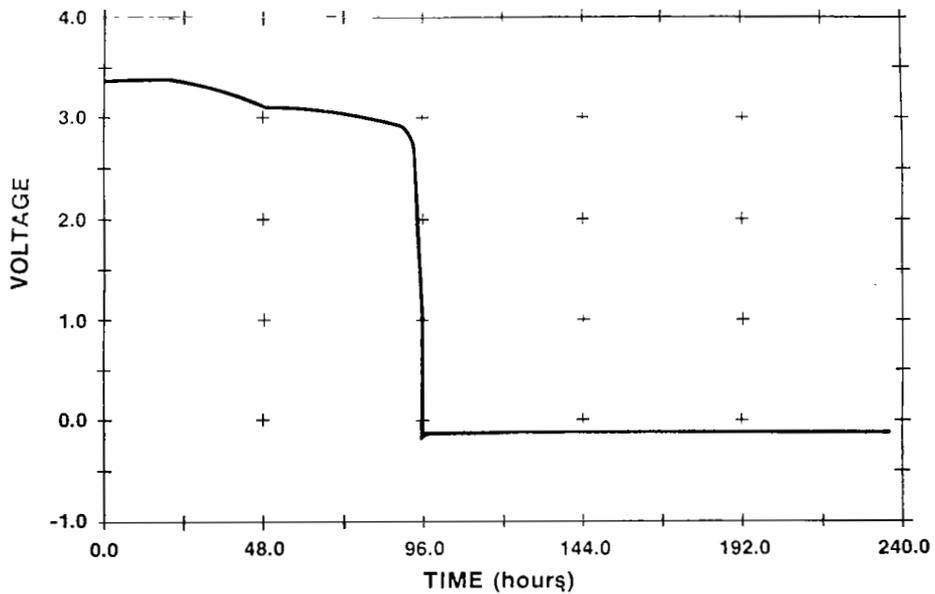
### TYPICAL DISCHARGE CURVE WITH TEMPERATURE



0 degree PERFORMANCE TEST, 22 AUG 79, 2 amp RATE  
 ALTUS AL-250, LITHIUM THIONYL CHLORIDE, SERIAL #187

Figure 2-6

### TYPICAL DISCHARGE PROFILE



0 degree PERFORMANCE TEST, 12 amp RATE, 3 OCT 79  
 ALTUS 17 inch CELL, LISOCL2, SERIAL #91 (3)

Figure 2-7

# TYPICAL APPLICATIONS OF LITHIUM PRIMARY CELLS

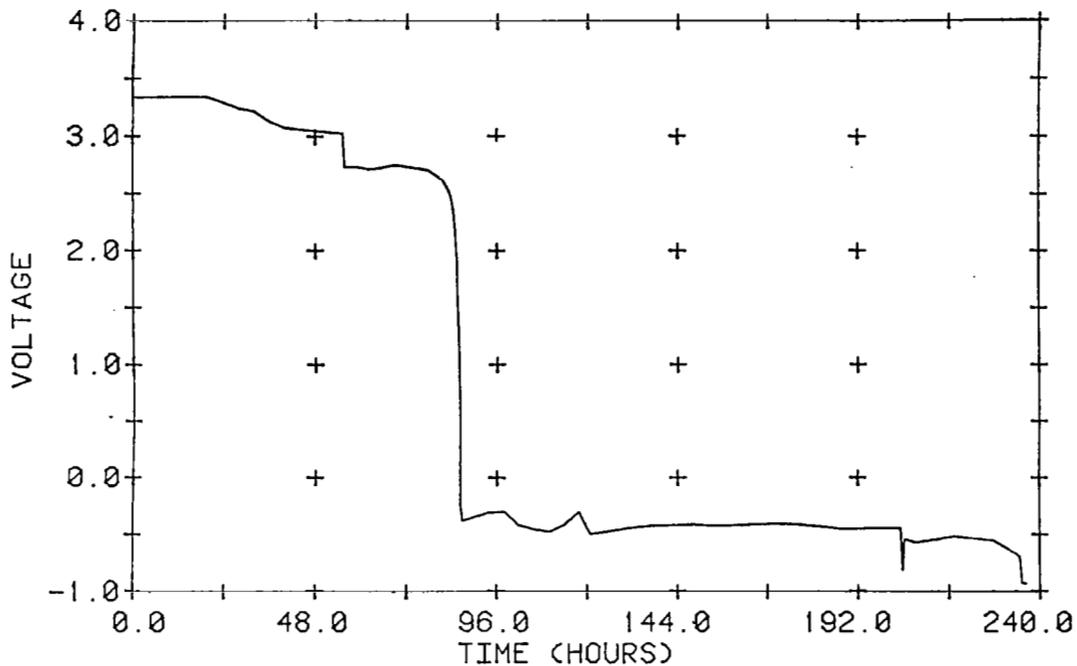
Application	Rates	Capacity (AH)
Remote sensors	Low	10-100
Countermeasures & decoys	High	10-100
Portable communications equipment	Medium	20
Vehicle propulsion	High	1000-3000
Sonobuoys	High	10
Targets	High	1000
Torpedoes	Very high	50-300
Mines	Low	500
Missiles	Very High	10
Ordnance fuzing	Very High	1
Data links	Low	100
Tactical data terminals	Medium	10
Standby power	Low	10-10k
Portable lighting equipment	Medium	20

Figure 2-8

TABLE 2. ACCEPTANCE INSPECTIONS & TESTS SUMMARY

CELL NO.	DIMENSIONS (IN.)				WEIGHT (LBS.)	OPEN-CIRCUIT VOLTAGE	SURFACE PH LEVEL (ppm)	WORKMANSHIP	COMMENTS
	DIA. O.D.	DIA. I.D.	THICK-EDGE	THICK-BULGE					
89	17.0	2.658	1.40	1.65	29.55	3.636	5	OK	Leakage from Vent. Reject
91	17.0	2.655	1.409	1.629	29.175	3.644	5	OK	Passed
94	17.0	2.658	1.40	1.625	28.89	3.632	5	OK	Passed
95	17.0	2.658	1.398	1.637	29.23	3.625	5	OK	Passed
100	17.06	2.660	1.410	1.672	29.41	3.621	5	OK	Passed

Figure 2-9



0 DEGREE C PERFORMANCE TEST, 12 AMP RATE, 3 OCT '79  
 ALTUS 17 INCH CELL, LISOCL2, SERIAL #94

Figure 2-10

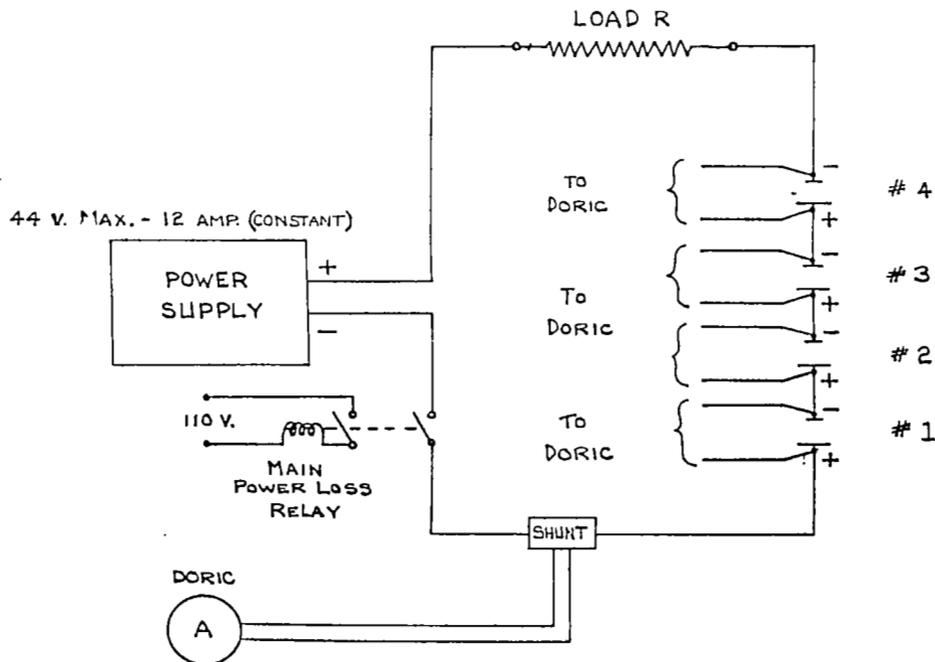


Figure 2-11



## GALILEO LITHIUM/SO<sub>2</sub>

L. Blagdon  
Honeywell

I would like to present today the general requirements of the Galileo lithium SO<sub>2</sub> battery, the current status on that program, as well as some general comments relative to the experiences we have already gone through in the development of that battery.

I will start, first of all, with the discussion of a general review of the specification requirements for this device.

(Figure 2-13)

First of all, it is a modular concept. The full battery is three modules. Our responsibility is for developing a single module which, in the system, three modules will be hooked in parallel and the diode isolation of those modules is included in the systems design.

The electrical characteristics required are 7.2-ampere hour minimum capacity at a minimal voltage of 28.05 volts. That is being accomplished with 13 high-rate D cells.

Capacity from module to module must be within 5 percent of each other in lot acceptance testing. Voltage delay requirements are required less than 100 microseconds voltage delay to 28.05 minimum voltage. Single point failure requirements required that bypass diodes, shunt diodes be placed on each cell in the series connected string.

The batteries also required to have a pyrotechnic tap in the 14- to 24-volt range, which runs up at about 7 amperes for 30 milliseconds. The actual discharge rate or discharge profile for the battery runs anywhere from a cruise timer load of 0.5 milliamperes on the module for 150 days up to 3.27 amperes at the end of discharge life, or at the end of the mission. And there are a number of steps between there as additional testing equipment comes on line.

The storage requirement is 5.4 years, basically under a controlled environment of 0°C. There is some 40°C requirement during some uncontrollable chipping times or while it is on the launch pad. But something over 4 years of that time is spent at 0°C.

Specification also requires that during that time there is 2.5 percent per year maximum, 2.5 percent per year capacity loss.

Reliability predictions required are 0.99 probability of completing the mission. The mission is defined right now at 6.65 ampere-hours. So, the total mission is under the minimum ampere-hour capacity requirements.

(Figure 2-14)

The basic configuration of the module is a rigid vented case that has to support its environment, mechanical environment in a beam type of mounting configuration. I have got a drawing a little later showing the general configuration of the module, and you can see what I am talking about there.

Maximum weight is 2.5 kilograms. Environments that it must survive are both sine and random vibration. Deceleration is at 410 gs for 30 seconds. There is a 150-g lateral shock load and a 30-grms random vibration requirement that the module must survive. It also must survive a low-rpm spin around the center of gravity of the probe. It must withstand radiation exposure, cobalt 60 up to 200 kilorads, and a pressure on entry into the Jupiter environment. Qualification is 16 bars, and acceptance is 13 bars.

(Figure 2-15)

Basic cell configuration used is a high-rate D cell jelly-roll configuration active, hermetically sealed. The header is laser welded into the case. Case and header materials are 304 stainless steel. The glass-to-metal seal uses a tandem feed through. The cell is lithium limited, that is a little bit of a misnomer. It is designed as a coulometrically balanced cell. So the stoichiometry of the thing is balanced between the SO<sub>2</sub> and the electrolyte with excess collector capacity from a dump-site point of view.

The cells do have safety vents in them, and have a relatively high surface area, active surface area.

(Figure 2-16)

Thirteen of these are mounted in a package that is approximately 13-1/4 inches long, and flange mounting occurs at the brackets on both ends. The brackets are attached to an arm which is supported off pivot point so that the entire device is suspended by those brackets and must withstand all the environments in all three directions.

The cells are stacked, as you can see, 13 of them. All the diodes and thermistors – there are two monitoring thermistors in there – are mounted on a flexible printed circuitboard that is manufactured to NASA's specification.

The shunt diodes are procured to a Marshall Space Flight Center specification for very, very low reverse current drain rates, because they have to stay on there 5 years. And we certainly cannot lose too much capacity from them.

The case is aluminum. It is of single-unit construction and is machined from a single block of aluminum. Connectors are in both ends. One is an instrument connector; the other is the power connector.

The battery in its current configuration does not have a fuse built into the battery. For shipping and general handling purposes, a special cap has been designed to be left with the battery

and mounted to the battery on one of the connectors. That does fuse the output leads or the power leads on the battery.

In its actual mounting location in the probe, it would not be fused. The primary considerations in that design choice right now is with respect to reliability. However, that is being reconsidered currently. We may, in fact, put a fuse in the actual unit.

(Figure 2-17)

To date, the electrical performance that we have demonstrated utilizing five cells stacked, series connected stacks. The mission has a rather sophisticated temperature profile also.

During the cruise portion of the mission, the minimum temperature is  $-5^{\circ}\text{C}$ . The five-cell stacks delivered 7.26 ampere-hours at the minimum temperature profile, or to the minimum temperature profile, which actually on entry drops down to  $-14^{\circ}\text{C}$  and then comes back up.

At a nominal or average temperature profile for the mission, the cell stacks delivered 7.73 ampere-hours, and at the maximum temperature the cell stacks delivered 7.79 ampere-hours.

The cells basically are not thermally insulated from the environment, and the thermal analysis of this module configuration says that the battery and the cells will track very closely the external environment that the probe is seeing. So, these tests were conducted without a great deal of thermal insulation around them, which generally adds to their overall capacity.

*Minimum Pyropulse Voltages.* – At the end of mission, which is an additional 7-ampere 30-millisecond pulse on the battery, would leave you with battery voltages as shown, 33, 32, and 31 volts, based on the different mission temperature profiles.

*Voltage Delay.* – Voltage delay requirements are 100 microseconds. Generally, there were problems in meeting that. There were systems design changes to include or add a preconditioning load before entry, and before the entry load profile begins to take place to clean the cell up.

The results of that testing indicated that a 1-ampere load for about 5 seconds would clean that, any passivation that was on the cells, up, and eliminate any problems with meeting that voltage delay requirement.

(Figure 2-18)

*Storage.* – There has been a little bit of accelerated storage test work done relative to the hermetic seals. However, 450 cells are going under  $0^{\circ}\text{C}$  storage environment, which is a real-time storage environment. Because of a stretchout of the program by about 2 years, we will have about 4 to 4-1/2 years of real-time data on this cell hardware.

The cells are evaluating the effects of the bypass diodes on storage as well as effects of orientation or the zero-g in the environment, so there are about three different configurations that are going into that test. The cells are being completed this month and will go on storage this month.

The other thing relative to storage, a protective cap has been designed for the glass-to-metal seal. There was at accelerated temperature, some corrosion of the glass-to-metal seal, or the glass in the glass-to-metal seal witnessed, and the protective cap is included on the hardware to basically take away the effects of orientation, which appear to be the primary difference in any corrosion rates that we have seen. In high-temperature inverted storage cell test, it has done an effective job. The cap has done an effective job in correcting it.

*Reliability.* – We did make a preliminary prediction of 0.99 probability of completing the mission, or the 6.65 ampere-hours. Basically, the way we accomplished that was with the excess capacity in the fact that a single cell could be lost at the 6.65 ampere-hour point, and the module would still be above the minimum voltage requirements in the program.

(Figure 2-19)

The first module is completed. It was completed this month. The actual weight of the unit was 2.2 kilograms. And we are in the process of completing five additional modules that will be subjected to the mechanical environments required.

Cells from phase 1 of the program have passed random and sinusoidal vibration and deceleration, both as individual tests and as sequential tests. And non-Galileo cell hardware of a similar construction has passed the radiation requirements.

Now I would like to make a few comments based on the experiences that we have run into so far in the development of this battery.

(Figure 2-20)

We believe from a safety point of view that the battery designs should be vented to design – and the original Galileo program did spec a sealed module to withstand the venting of individual cells. That was eventually changed, and the present module configuration is vented. We believe from a safety point of view that is necessary.

Isolate diodes should be used if parallel configurations are required. I think that is pretty standard at this point in time. That is part of the system as far as the way our program is put together.

The batteries should be fused. Cell designs, we believe, should be lithium limited, or at least coulometrically balanced in lithium and sulfur dioxide ratios.

We believe the people who will be eventually handling and operating these cells do need clear training and understanding of what they have in their hands. The battery module or concept should be incorporated in high-energy requirements. And by that I mean we do not believe that batteries should be built containing excessive amounts of cell hardware, large cell quantities in a single battery configuration. They should be split up into smaller, more handleable packaging-type configurations.

(Figure 2-21)

And lastly, from a reliability point of view, we feel that there is possibly some additional work that can be done in optimizing the voltage and capacity requirements to ensure that you can withstand a single cell failing within a battery, still meeting the minimum voltage requirements.

If you specify and order a four-cell battery, it is going to be very, very difficult to make 0.99 reliability predictions based on the analysis we have run so far. Single point failure can be eliminated, and it is almost a must in the high-reliability configuration.

The impact of that, of course, or the question that comes from that is relative to the losses in storage that might be incurred with the bypass diodes, which are currently undergoing tests to determine – by the way, those leakage currents for those specific diodes are in the nanoampere range.

*Performance.* – Cell manufacturing tolerances must be tightly controlled. We found some of the standard raw materials coming for our cell hardware are not adequate to meet the kind of tolerances that we are looking at for some of these applications.

Battery conditioning should be considered if there is a severe voltage delay requirement in the microsecond range. We do have long-term storage.

And again, if a long-term storage requirement is involved, control in temperature environment is very, very important in guaranteeing that you meet your storage requirements.

## DISCUSSION

MAHY: You never did tell us what the end use discharge current was.

BLAGDON: Actual load profile ranges from 0.5 milliampere on a module for 150 days on the front end, and winds up with full instrumentation on it about 3.27 amperes. End of life occurs under 3.27-ampere load.

MAHY: There is continuous use in a way over the whole 5.4 years?

BLAGDON: No. Basically, it is turned on 150 days prior to entry. During the other 4 years, it is under storage, or just inactive.

TATARIA: You said your cells are hermetically sealed. How are you taking hermetic sealing, the outside leak rate or the helium leak rate?

BLAGDON: We use the helium leak rate and a very high sampling plan on a hardware that we are currently building, the cell hardware that we are currently building to ensure that we have that. We also do 100 percent sort of all the glass-to-metal seals.

TATARIA: You did the helium leak rate?

BLAGDON: On the finished cell? No, our normal procedures require a 48-hour heat soak and then visual examination.

We are looking at some other alternatives to determine if there is any additional weight loss at that time. Currently it is a heat soak, visual and weight measurements on the cells after they are manufactured.

TATARIA: Thank you.

WATSON: Would you care to comment on the cause of the glass seal corrosion that you discussed, and how your protective cap prevents that from occurring?

BLAGDON: Basically, I don't know whether the actual causes of the glass seal corrosion are specifically known and understood today. The protective cap simply uses an O-ring pressure-type seal on the inside to not allow the electrolyte in full contact, in the inverted position, and in full contact with the cells.

It is not a second hermetic seal. It is not intended to be. The purpose is simply to take away the effects of orientation in turning the cell upside down and to reduce the amount of ionic activity that can be taking place there at that surface.

And it is accelerated, or high-temperature inverted storage tests of that cap indicate that it is doing a very nice job. It does not stop all corrosion, by the way, at the high temperature, but it is doing a very nice job.

SEITZ: I believe it was mentioned this morning that an alternate system is being considered for Galileo. Is that true?

BLAGDON: I don't think so. I don't recall that being mentioned. I guess you would have to talk to Hughes if you want to find out about that. I don't think so.



MODULE DESIGN REQUIREMENTS

ELECTRICAL CHARACTERISTICS

- . 7.2 AHR. MINIMUM CAPACITY
- . 28.05 TO 39.0 VOLTS
- . CAPACITY WITHIN 5% WHEN DISCHARGED TO 28.05 V
- . VOLTAGE DELAY <100 MICROSECONDS
- . SINGLE POINT FAILURE PROTECTION VIA BY-PASS DIODES
- . PYRO TAP FOR 14-24 VOLTS

STORAGE

- . 5.4 YR. LIFE
- . 2.5% PER YEAR MAXIMUM CAPACITY LOSS

RELIABILITY

- . 0.99 FOR COMPLETING THE MISSION

Figure 2-13



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MODULE DESIGN REQUIREMENTS (CONT'D)

MODULE

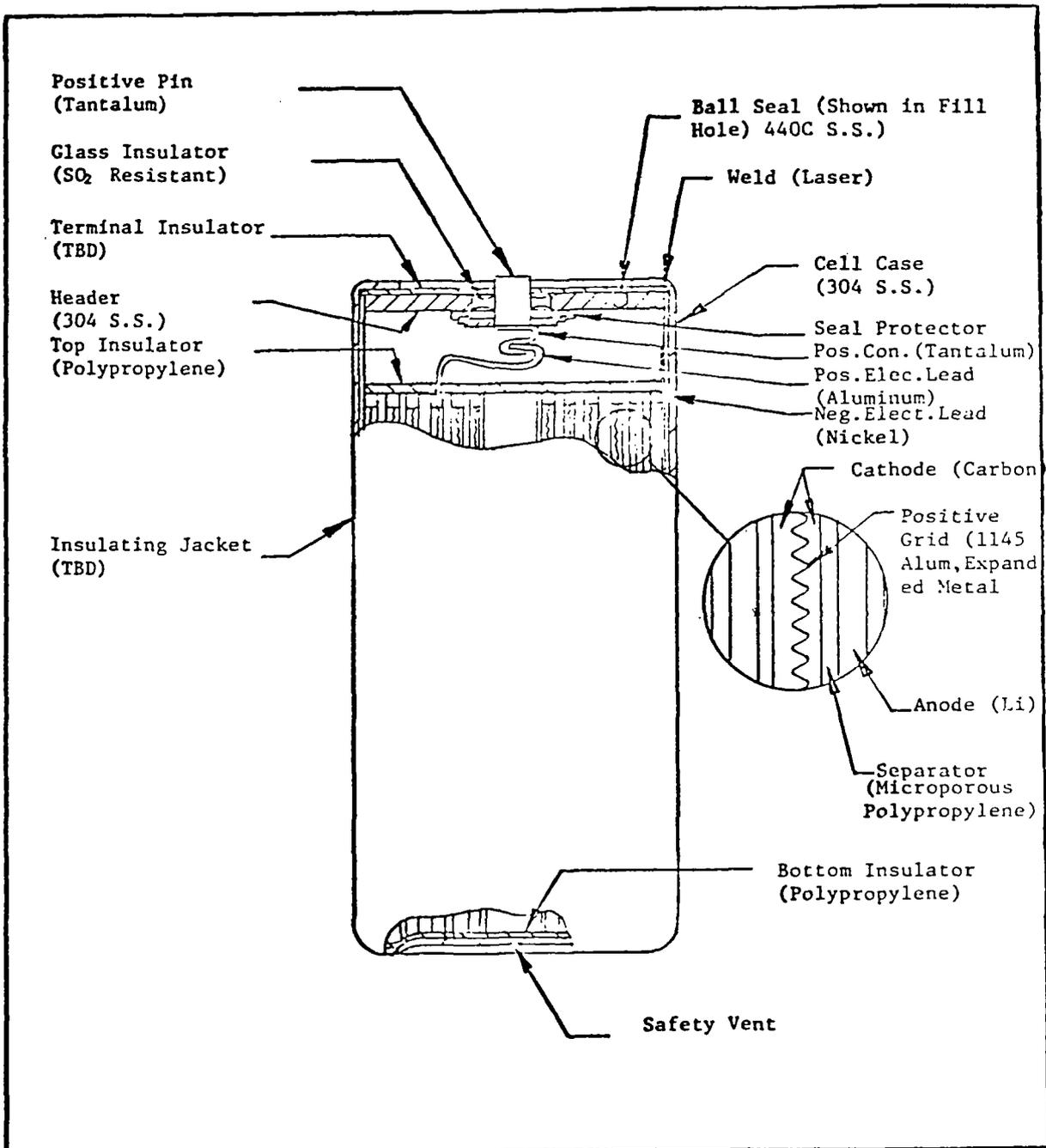
CASE - RIGID VENTED  
- MAXIMUM DEFLECTION - 0.050 INCHES  
- FINISH 0.1

MASS - 2.5 Kg MAX.

ENVIRONMENTS

- . VIBRATION - SINE AND RANDOM VIBRATION
- . DECELERATION, 410 G's
- . 150 G's LATERAL, 30 RANDOM VIBRATION
- . SPIN 10-15 RPM, 2.5 - 5 RPM
- . RADIATION 200 KILORADS Co<sup>60</sup>
- . PRESSURE, 16 BARS QUAL; 13 BARS ACCEPTANCE

Figure 2-14



FOHM FM-100

PARTIAL CROSS SECTION OF HONEYWELL  
BASELINE CELL

Figure 2-15





ELECTRICAL PERFORMANCE

- DEMONSTRATED CAPACITY TO 28,05 VOLTS BASED ON DISCHARGES OF 5 CELL STACKS:

<u>MISSION TEMP. PROFILE</u>	<u>CAPACITY (AHRs)</u>
MINIMUM	7.26
NOMINAL	7.73
MAXIMUM	7.79

- MINIMUM PYRO-PULSE VOLTAGE AT 6.65 AHRs (END OF MISSION):

<u>MISSION TEMP. PROFILE</u>	<u>VOLTAGE (VOLTS)</u>
MINIMUM	31.3
NOMINAL	32.0
MAXIMUM	33.0

- VOLTAGE DELAY - MET BY APPLYING A CONDITIONING LOAD WHICH REQUIRED AN ELECTRICAL SYSTEM CHANGE.

Figure 2-17



STORAGE -

- 450 CELLS TO BE STORED AT 0 °C CONFIRMING THE EFFECTS OF ORIENTATION AND BY PASS DIODE LEAKAGE CURRENT, ON TEST Nov. 1979.
- PROTECTIVE CAP OVER CELL GTM SEAL HAS MINIMIZED EFFECTS OF ORIENTATION (OR 0 G ENVIRONMENT) BASED ON 70°C INVERTED STORAGE TEST RESULTS.

RELIABILITY

- 0.99 PROBABILITY OF COMPLETING MISSION (6.65 AHRs.) HAS BEEN PREDICTED.

Figure 2-18



MODULE

- FIRST PROTOTYPE MODULE COMPLETE 7 Nov. 1979
- ACTUAL WEIGHT OF FIRST MODULE - 2.22 KILOGRAMS.
- FIVE ADDITIONAL MODULES IN PROCESS TO BE ENVIRONMENTALLY TESTED.

ENVIRONMENTS

- GALILEO CELLS (PHASE I) HAVE PASSED THE FOLLOWING SPECIFICATION ENVIRONMENTS:
  - RANDOM VIBRATION
  - SINUSOIDAL VIBRATION
  - DECELERATION
- NON-GALILEO CELLS (SIMILAR CONSTRUCTION) HAVE PASSED THE RADIATION REQUIREMENTS.

Figure 2-19



SAFETY

- BATTERY DESIGNS SHOULD BE VENTED
- ISOLATION DIODES SHOULD BE USED IF PARALLEL CONFIGURATIONS ARE REQUIRED.
- BATTERIES SHOULD BE FUSED.
- CELL DESIGNS SHOULD BE LITHIUM LIMITED.
- DEFINE OPERATION HANDLING AND TRAINING PROCEDURES.
- BATTERY MODULAR CONCEPTS SHOULD BE INCORPORATED FOR HIGH ENERGY REQUIREMENTS.

Figure 2- 20



### RELIABILITY

- OPTIMIZED BATTERY VOLTAGE/CAPACITIES TO WITHSTAND SINGLE CELL FAILURE.
- SINGLE POINT FAILURE CAN BE PRECLUDED WITH BY PASS DIODES.

### PERFORMANCE

- CELL MANUFACTURING TOLERANCES MUST BE TIGHTLY CONTROLLED.
- BATTERY CONDITIONING SHOULD BE CONSIDERED IF VOLTAGE DELAY IS CRITICAL.

### STORAGE

- CONTROLLED (LOW TEMPERATURE) ENVIRONMENTS ARE CRITICAL IF LONG TERM STORAGE IS REQUIRED.

Figure 2-21



## SULFUR STUDIES ON LITHIUM SULFUR DIOXIDE BATTERIES

A. Dey  
Mallory

Lithium SO<sub>2</sub> batteries are being manufactured in substantial numbers now by various companies and have been sold for several years now.

So there are a lot of users who use these batteries in various ways and try to extract as much as possible in terms of energy. Of course, when one does that, he occasionally runs into various problems. That is a subject that we studied for the last year or so.

The work started initially after we hired Thrombani of NASA. He was trying to use SO<sub>2</sub> D-size batteries at -30 degrees on 2-ampere force discharge, and he found some of the cells caught fire, and so forth, under these kinds of conditions. It was forced-discharge problem that occurred.

Well, when we started to study the problem, we decided that we wanted to look at it as comprehensively as possible, look at the chemistry of the system, try to learn more about the chemistry, and solve chemically as well as by other engineering means. So I will start with some of the work that we have done using DTA off lithium SO<sub>2</sub> battery chemicals.

(Figure 2-22)

The first figure shows DTA of lithium and SO<sub>2</sub> by themselves. Lithium is the anode active material, and SO<sub>2</sub> is the dipolarizer. Of course, we want to know how stable they are.

As you see, this is the heating curve here. This endotherm corresponds to melting of the lithium, and then we continue the heating to 320 degrees. In some experiments, we have increased that to 350 degrees. As you note, there is no exothermic reaction between the two very reactive materials. These are the materials which give you the energy of the battery.

This is a cooling curve where you see again that the lithium is freezing off, and again there is no reaction. That demonstrates the protective nature of the film which is the product of these two product of the cell reaction which is lithium dithionite, a solid crystalline material which coats the lithium as soon as these two are mixed. That coating is sufficiently stable so that even under such extreme conditions of heating, nothing happens. So lithium and SO<sub>2</sub> is very stable.

Next, we did the DTA of lithium and acetonitrile which is the organic solvent compound of the electrolyte. The DTA is shown in the next figure.

(Figure 2-23)

The figure shows the lithium and acetonitrile. As you see, it is very, very reactive, and it reacts even at room temperature. In fact, here, the initiating temperature is roughly 58 degrees. If you have very little lithium, you may see them react with heat evolution even at room temperature. Of course, the amount of heat generated is quite significant to cause hazard.

So, these are the two components the most responsible for all the behavior, all the unsafe behavior that we heard and we saw ourselves.

One of the things I think I should point out is that exotherms initiate at a certain temperature when you heat it up. That is the good parameter which determines the stability of the system. So, we use that parameter to develop alternative electrolytes. The lower the temperature of this exotherm initiation of this reactive reaction, the more unsafe the situation is. We would like this to occur at the highest temperature possible in an actual cell.

In the next figure, we show the DTA of the lithium, and the electrolyte.

(Figure 2-24)

The electrolyte consists of acetonitrile,  $\text{SO}_2$ , and lithium bromide, 70 percent of  $\text{SO}_2$ .

You notice again the heating, the initiation of the exotherm occurs at 170 degrees. It has been increased from 50 degrees or so, which you saw in lithium acetonitrile to 170 degrees.

This exotherm is due to the lithium and the acetonitrile. Just as in the presence of  $\text{SO}_2$  that temperature is increased, so the lithium  $\text{SO}_2$  battery will be able to sustain this kind of temperature, but no more. If you go beyond that, you will have a problem.

We have looked into the possibility of developing alternate electrolytes into which the exotherm initiation temperature is going to be. So, it is actually higher than what we find with lithium acetonitrile by themselves. You have noticed that the  $\text{SO}_2$  electrolyte contains  $\text{SO}_2$ . The presence of  $\text{SO}_2$  itself has done a tremendous improvement, 70 percent  $\text{SO}_2$ .

We are interested in finding out what is the lowest concentration of  $\text{SO}_2$  needed for lithium acetonitrile reaction to be suppressed. That we did by measuring the exotherm initiation temperatures of the lithium acetonitrile, those two complements, as a function of  $\text{SO}_2$  concentration. That is shown in the next figure.

(Figure 2-25)

Here are the exotherm initiation temperatures in degrees Centigrade. These are temperatures at which the exothermic reaction begins between lithium and acetonitrile. And we are adding  $\text{SO}_2$  in that solution. Here is the percentage of  $\text{SO}_2$ . When there is no  $\text{SO}_2$ , the exotherm is initiated as you see, roughly 50 degrees, or thereabouts, a very unsafe situation.

So, if you have a cell where all the  $\text{SO}_2$  is consumed, obviously you can expect that cell to behave in an unsafe manner because of the lithium energy problem. But, as you add  $\text{SO}_2$ , note that even at high percent  $\text{SO}_2$  in the cell gives you quite a bit of protection. The cell can stand quite high temperatures before it can generate exothermic heat, causing all kinds of problems.

Of course, we have completed the experiments of in transial moisture. As you see, these points, adding 1 percent moisture. It does not seem to make that much difference between addition of 1-percent moisture and no addition at all, because moisture there also has some protective action. At least it does not have a deleterious action in that sense in these kinds of concentrations.

We did the experiments with lithium powders, and there you see you need quite a bit, almost 25 percent or so, to get protection. Lithium powder, of course, will have a very high surface area, and there, if you do not have sufficient amount of  $\text{SO}_2$ , you may see exothermic initiation at an earlier stage.

So these studies tell us that one must have design cells so that during their use and abuse there should be sufficient  $\text{SO}_2$ , at least 10 percent or so present in the cell which will protect the lithium that is left over, or lithium powder, or any other lithium products generated during the cell use and abuse.

(Figure 2-26)

Now this figure shows similar kinds of data. Instead of  $\text{SO}_2$ , we have used a second organic solvent with acetonitrile, so again we show the exotherm initiation temperature as a function of concentration of a second organic solving, which is very protective. Probably carbonate is in one instance, and acetic hydride in another. Both of these solvents, when added to acetonitrile, provide protection to lithium as evidenced by the increase in exothermic initiation temperatures. These are the temperatures at which lithium acetonitrile will react exothermically.

Again, you notice the 5 percent, or 5 to 10 percent, of this second solvent is sufficient to give protection to lithium, and hence potentially can provide the same for a cell.

We have tested a whole variety of organic solvents as additives and developed six different organic electrolytes which have conductivities similar to the conductivity of the standard electrolyte containing acetonitrile and lithium bromide.

Of these six, I believe two of them did not have any acetonitrile at all. Since the conductivities are very comparable, we have good reason to believe the performance of these cells probably will also be comparable.

We are now in the process of testing these in actual cells for storage and for performance at low temperature as well as for safety, and I hope that we shall be able to report on that soon.

Now one can look at the lithium  $\text{SO}_2$  battery as a whole as if it were an alternative system. It has three basic reactive components: lithium,  $\text{SO}_2$ , and acetonitrile. So, from design of safe cell,

one can then look into this alternative diagram and can come up with certain approaches to make safer batteries.

(Figure 2-27)

In this figure we show an alternative phased diagram to explain this. We have the  $\text{SO}_2$  here, lithium here, and acetonitrile here. So, in a battery when it is made, the composition of these three materials will fall along these lines when the battery is made. These are all the possible stoichiometric conditions that you can think of that will fall in this line.

Now one can, by design, make the batteries so that the composition falls somewhere around here. If it is somewhere around here to begin with, when you discharge the battery, one consumes both  $\text{SO}_2$  and lithium in a very, very predictable manner based on  $\text{SO}_2$ .

Now, that has been established very well. The reaction is also very efficient, 100 percent efficient. As you discharge the cell, the composition inside the cell of these three materials changes in a manner such as this. Therefore, at the end of the discharge, you end up somewhere around here.

Now, when you end up here, this is a condition in which you do not have any lithium left. All the lithium is gone. You have plenty of  $\text{SO}_2$  left, and you have plenty of acetonitrile. This is then a lithium-limited design, as you have heard mentioned earlier, a design according to what we have talked about, a safer situation.

On the other hand, if you are here, then as we discharge the cell, you move in this direction, you end up with a situation where you do have some lithium left, and you may or may not have  $\text{SO}_2$  left, depending on where you are. In fact, here you have no  $\text{SO}_2$  left, and therefore you would expect the unsafe behavior ensuing because of the action between lithium and acetonitrile, as we have been illustrating.

So this is then a design which has excess lithium. This, of course, assumes that the efficiency of discharge of  $\text{SO}_2$  is 100 percent.

Now, as you know,  $\text{SO}_2$  is discharged at carbon cathodes. Depending on the activity of the carbon cathodes, you may or will not use all of the  $\text{SO}_2$ . The efficiency of utilization of  $\text{SO}_2$  may vary depending on the quality of the cathode or the amount of carbon in the cathode and so forth. So, that is another parameter that one has to consider for a safe design of  $\text{SO}_2$  battery.

Now, from all of this we can say that we do know quite a bit about the system. It is highly predictable because of what we have found, and therefore we can design the cell to take all kinds of abuse and use conditions.

To give you just two examples of the forced discharge that I mentioned in the beginning.

(Figure 2-28)

In this figure, I show in voltage and temperature profile, a D cell which is forced discharge at -30 degrees at 2 amperes.

This is a cell which contains excess lithium by design. You will notice here, this is the voltage, that is the temperature, and this is the number of hours, at -30 degrees at 2 amperes.

Notice initially you have a cell voltage of up to 1 volt. There is gradually a decrease and reaches zero volts. Now, if you had a reference electrode in this cell, you would find the cathode, the carbon cathode. These voltages are characteristics of the carbon cathode only. Lithium voltage remains constant. Lithium potential remains constant. It is the cathode which goes through this.

So, we know that above zero volt, all you are having here is basically reduction of  $\text{SO}_2$  primarily. Then, you reach 0 volt. Below zero volt, what you have here is also quite predictable. You are having deposition of lithium on your carbon cathode and on your aluminum exotherm.

Dr. Taylor in our lab demonstrated that, in fact, what you have is a lithium-aluminum alloy formation on the cathode in this area when the cell voltage is negative.

Also, notice that during this place when the cell is polarizing, of course, you are generating the energy that is not delivered, utilized in generative heat. So, you heat up the cell during the polarization phase. But, beyond zero volt, basically what you have is the deposition of lithium on your carbon cathode aluminum grid and dissolution of lithium on the anode, two reactions very reversible. Therefore, you have cooling basically, because you don't generate any heat. So, you are piling up a lot of this lithium-aluminum alloy and lithium dendroids during this phase.

Then, you reach a point, a very sharp reversal, and this is due to the fact that you have consumed all the lithium on the anode. There is no more lithium left; therefore, you polarize yourself severely, and that is the time when there is sufficient heat to cause this lithium material to get fired. We have a very rapid temperature buildup, temperature rise. Of course, this is the time when you have cell venting, sometimes violent venting and sometimes even fire.

So, because of all this activity when the cell is below zero volt, this occurs because of the excess lithium.

Now, if you design a cell so that the amount of lithium, the polarization of the lithium electrode is going to occur here instead of here, you just reduce the amount of lithium on your anode, and you make the cell go through this deep reversal at this point right here.

When that happens, there is not enough active lithium present to give you any problem. All you can see is venting or not venting at all.

We have tested many, many D cells with the lithium-limited designs at 2 amperes and -30 degrees and demonstrated this to be the case.

The next figure shows a typical voltage profile of such a balance, but a lithium limited cell. Assumption again is the same cathode in both cases.

(Figure 2-29)

Here is the voltage profile. You have about 2 volts for a while, and then it gradually declines. You see the voltage goes to deep reversal right at the point when the cell sees 0 volt. There is no chance for the formation of this active material I mentioned. You see that cells keep up at this point, and during the deep reversal you are wasting a lot of energy. That energy must show up somewhere. It is showing up, but it is not sufficient to give you any problem.

The cell either vents and, in fact, in most instances there is no venting at all. So, then by design, one can make these cells undergo all kinds of abuse, including very severe discharge, without any problem.

Another thing you must remember is that this characteristic, the number of hours that the cell is going to give you above 2 volts under a specific load, depends on the carbon cathode, a very important parameter. That is an area again where we have a tremendous improvement, although the cells do not vent at all.

A third possibility, also, perhaps I should mention, is that -- although I mentioned about the lithium-limited design and that, of course, has advantage not only from the forced discharge standpoint, but also from the point of view of disposal -- to establish that if you have lithium-limited design, you do not have formation of cyanide, and so forth, which certainly is an advantage.

(Figure 2-30)

But I must emphasize that all of these are dependent on current density of the total current. A cell, which is designed for 2 amperes and which can take that kind of abuse, if you increase the current to 5 or 10 amperes, this, of course will not be true. So the cells have to be designed for a particular current operation.

## DISCUSSION

BIS: I was a little bit confused when you did the electrolyte and the lithium, when you conduct the exotherm at about 200°C. Then you went ahead and did lithium, acetonitrile, and SO<sub>2</sub>; you showed a curve that got up to about 400°C.

DEY: No, 400 degrees. That is with the lithium SO<sub>2</sub>. 400°C, I am sure. It cannot be. Can you show the figure? I think you are talking about the one with the addition of SO<sub>2</sub>.

BIS: Right.

DEY: That's figure 2-24.

BIS: Now, you have got roughly 25 percent SO<sub>2</sub> in there, right?

DEY: Yes.

BIS: Now, your electrolyte is 70 percent SO<sub>2</sub>, is it not?

DEY: Yes.

BIS: What would your normal electrolyte composition on there be, assuming you eliminate the lithium bromide?

DEY: That was 70 percent. These are separate experiments. It is a good point. We did see some variation in that initiation temperature, depending on the specimens that you used, lithium specimens.

The experiments that we used earlier, we probably had some more active lithium specimens that may not have as much filler to begin with.

BIS: There is no lithium bromide in this, right?

DEY: No. That is a good point, too. Lithium bromide does catalyze some of these reactions, exothermic reactions.

BIS: That could lower the temperature?

DEY: *I think that is right.*

BIS: My second question is, basically have you done any chemistry, basic chemistry on these cells as a function of discharge rate storage? In other words, identification of species within the cells themselves?

DEY: We have done quite a bit, and we are continuing to do quite a bit of it. We expect to publish some of this soon. It is still in the works.

WATSON: Dr. Dey, in the lithium limited cell, you obviously don't utilize all the lithium at the end of your useful life. You are using the lithium as a current collector, so there is a certain percentage left over.

Do you have any feel for how much lithium is required before you enter the hazardous region?

DEY: If you do not have any current collector at all, then, of course, you have to have a finite amount. Now, what is the exact amount, I don't remember, what is the exact amount in terms of ampere-hour. But, there is a certain amount, and that will depend also on the design; how the electrodes are made, how it is connected, and to what it is connected. Because what

basically happens when you use the lithium up, you may not use it uniformly, depending on your cell design. If you don't use it uniformly, you may cut off a certain portion of lithium at a point very near the tab or near the connection. In which case, of course, you end up with a lot of lithium present.

So, care has to be exercised to how you design your anodes, how you connect it, and how uniform the reaction is to the spiral.

WATSON: One other thing. Why does it break near the tab?

DEY: Why? It will break if you don't design the cell properly. You may have reaction near the tab more than further away from it. That is strictly on cell design. This is very important.

ANGRES: I get the impression you tried to get away from acetonitrile.

DEY: Yes. And for obvious reasons, which is that it is a reactive component. It has some beneficial effect in terms of performance, but we are trying to see whether we can, in fact, get away from it or develop an electrolyte which can moderate its reactivity.

ZOLLA: Instead of a mechanism whereby you rely on the design according to the rate to safeguard you against this reverse voltage failure, would you not prefer to see a flat line design as seen in the previous paper whereby it is intended to break, and one does not have to worry about whether, in fact, one is sticking to the original design or just one parameter, one radius?

DEY: What design is that?

ZOLLA: The previous curve you saw shows the reverse voltage, as you entered reverse voltage, a flat line characteristic, which is independent of forced discharge rates.

I was just asking if you would not prefer to see that kind of characteristic in your cells.

DEY: Are you mentioning about the accounting battery where we are talking about?

ZOLLA: I know it is a different cell, but the same possibilities are there.

DEY: I wish that design were discussed in some detail, so I can make an assessment.

ZOLLA: I wish I could tell you all about it.

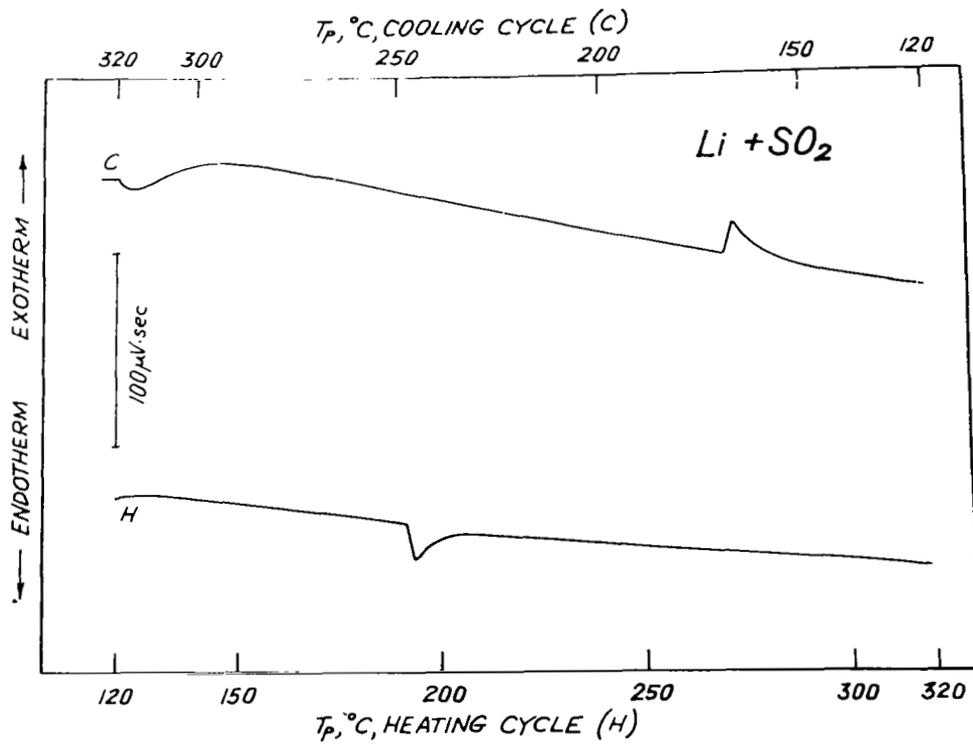


Figure 2-22

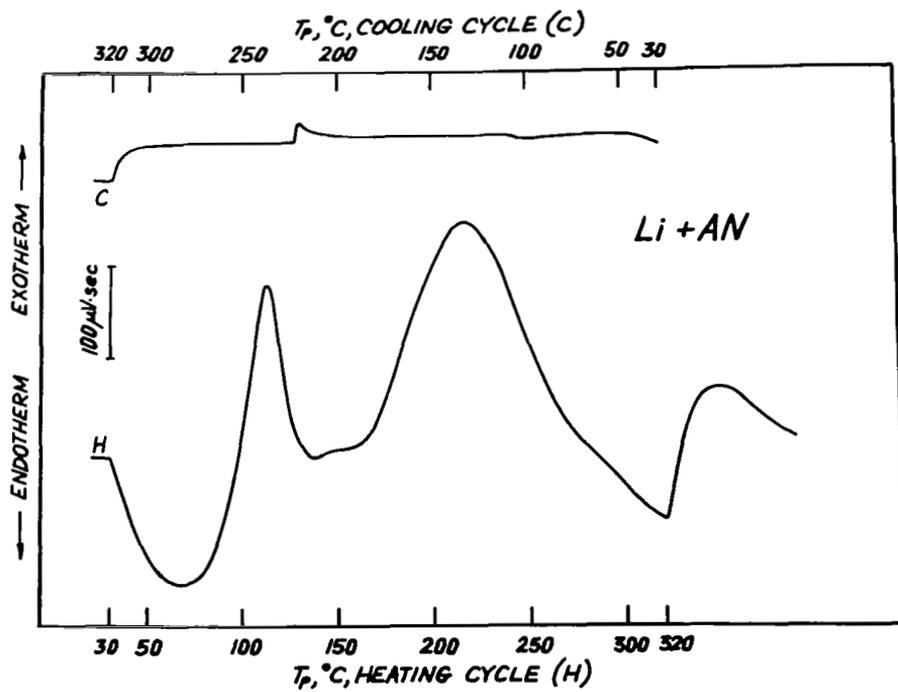


Figure 2-23

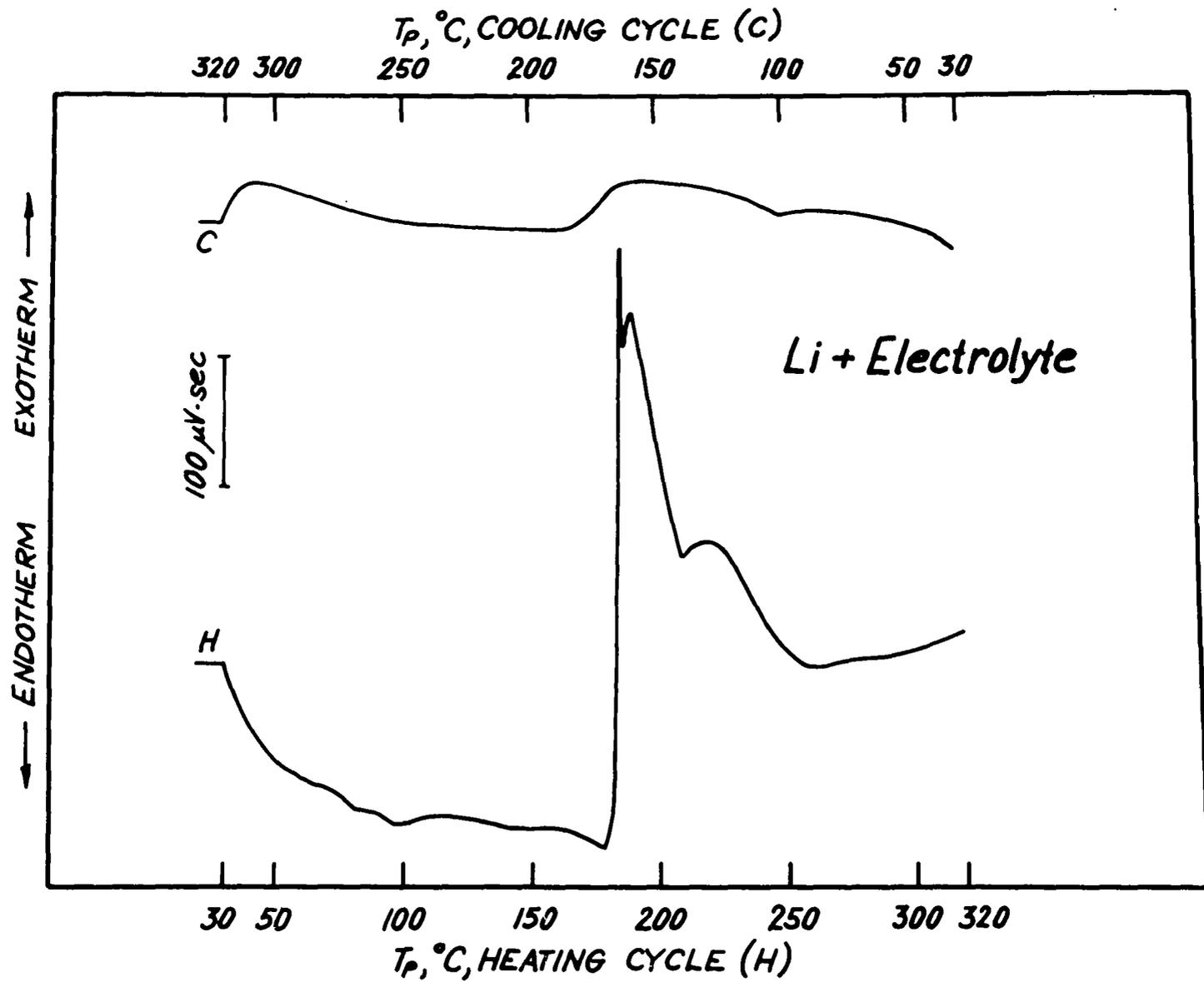


Figure 2-24

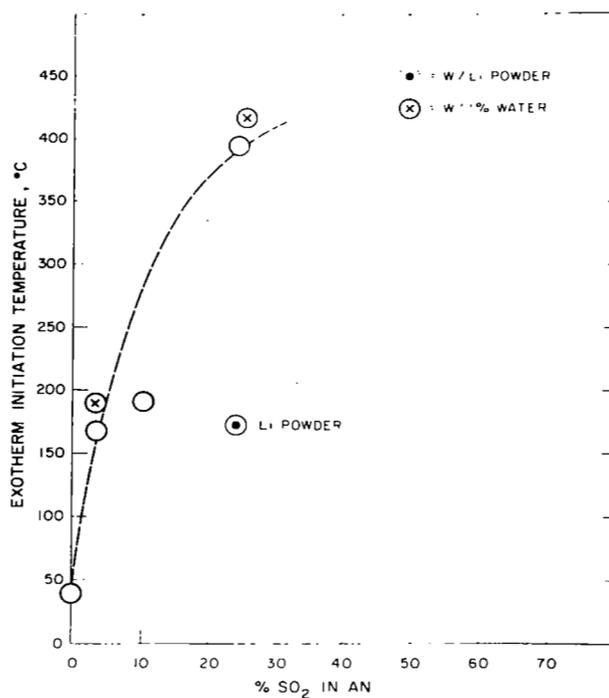


Figure 2-25

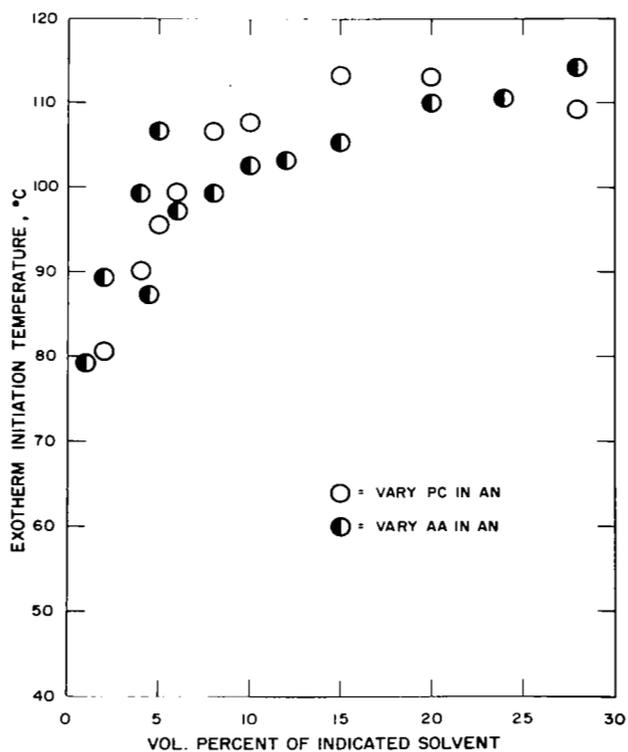


Figure 2-26

# Li/SO<sub>2</sub> DISCHARGE TRAJECTORIES

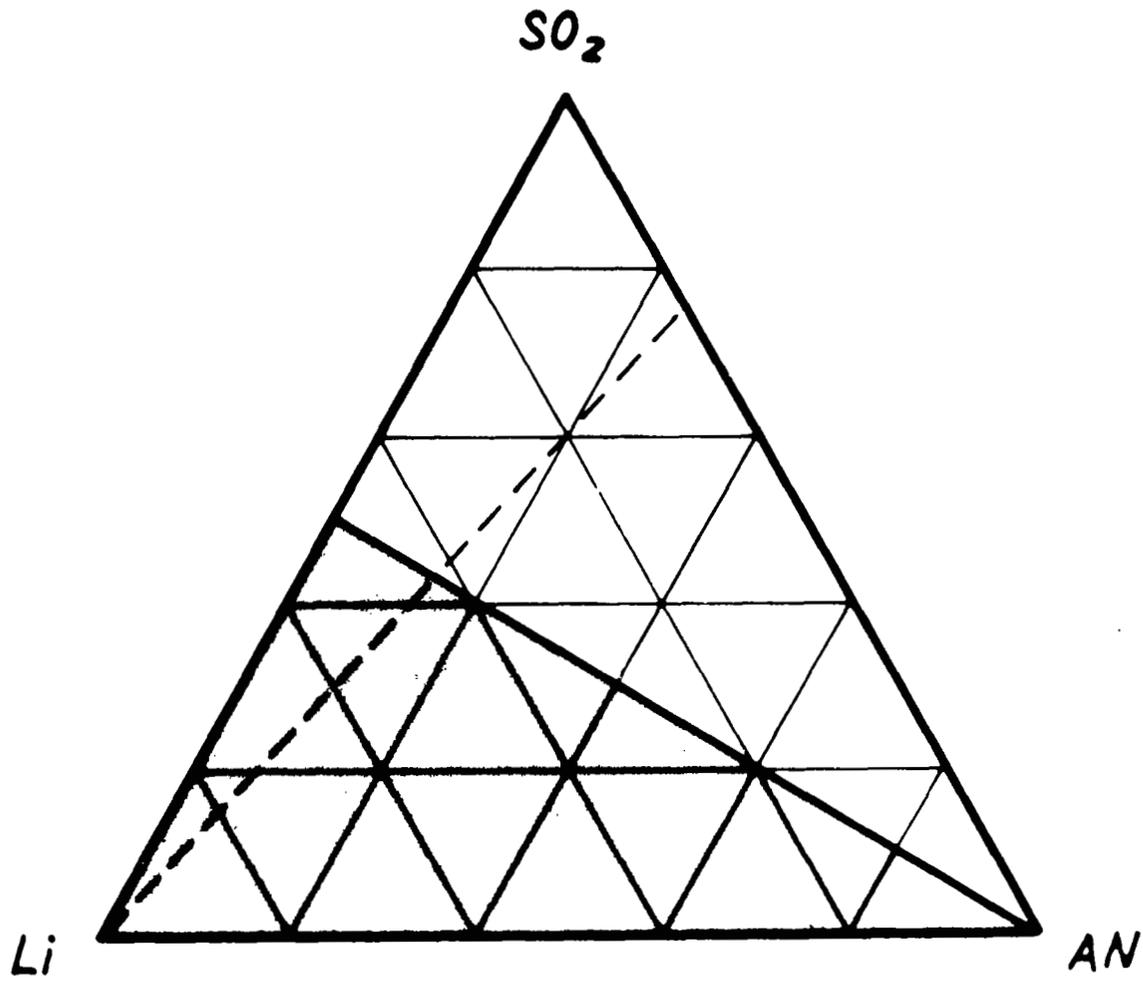


Figure 2-27

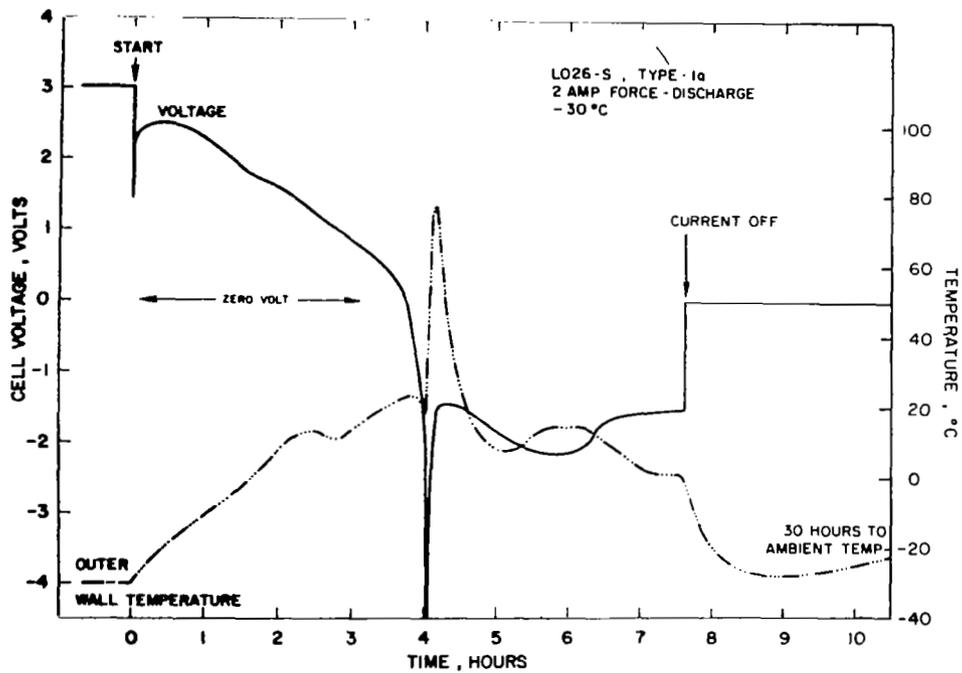


Figure 2-28

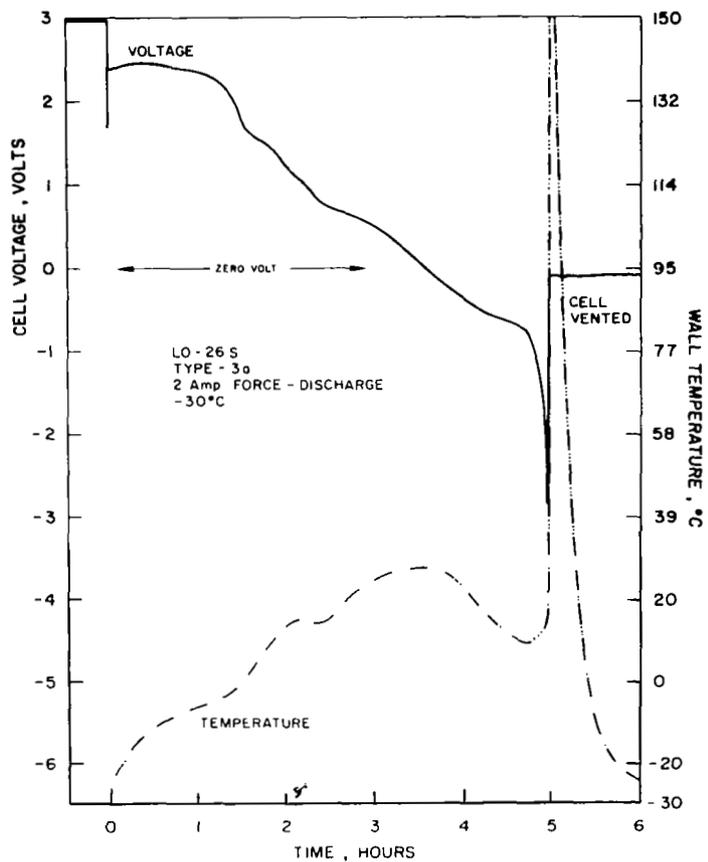


Figure 2-29

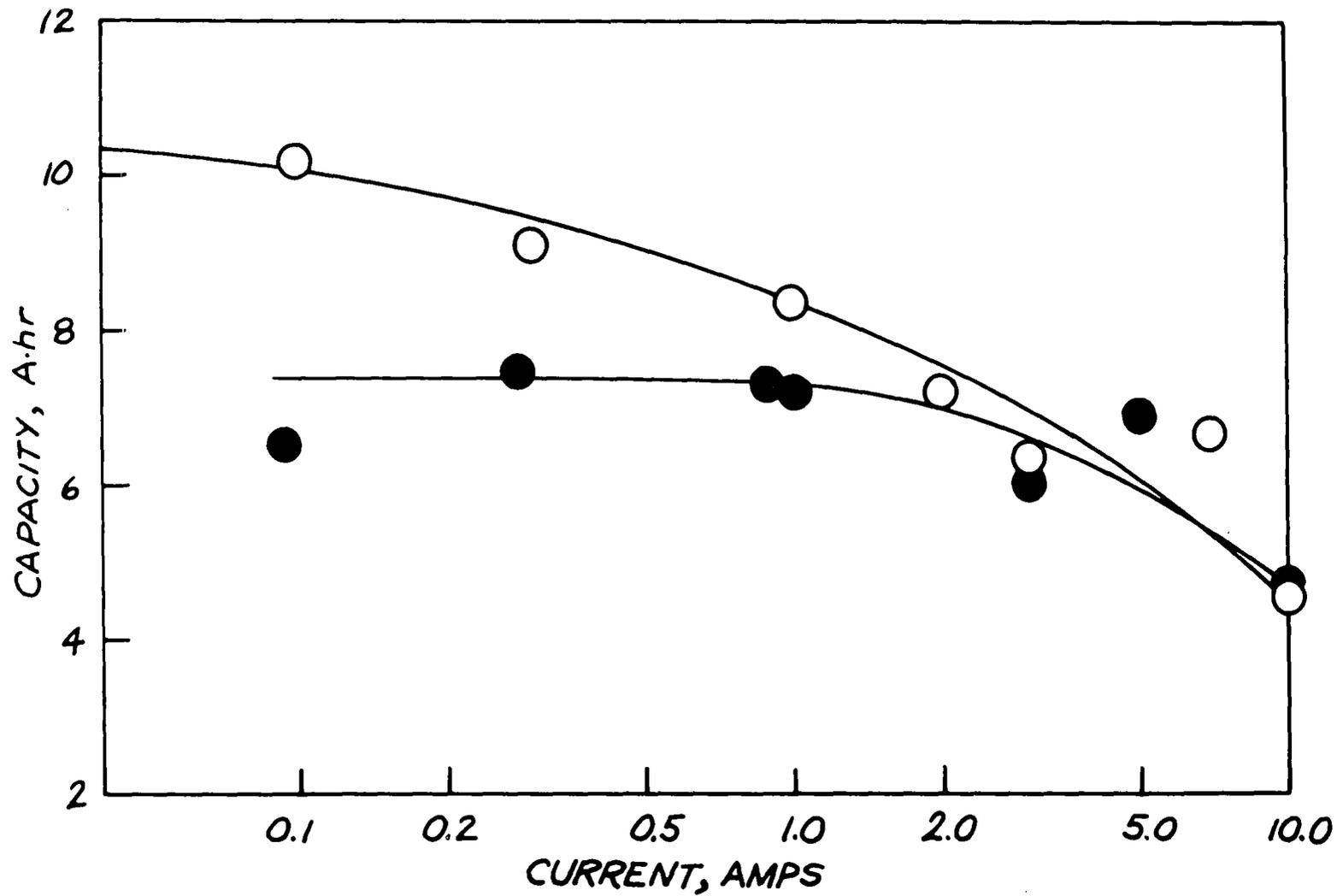


Figure 2-30

## ELECTRICAL, THERMAL AND ABUSIVE TESTS ON LITHIUM THIONYL CHLORIDE CELLS

R. Somoano for H. Frank  
JPL

I would like to discuss some of the electrical, thermal and abusive tests carried out on lithium thionyl chloride cells at JPL.

This work has been done by Harvey Frank. I am personally not associated with this program and do not know a lot about these materials. Nevertheless, I will encourage you to ask questions about any of the things I describe today. Although I probably cannot answer them, I will see that you get specific answers to those questions.

(Figure 2-31)

The next vugraph shows roughly what I will be describing. I will give you a description of the thionyl chloride-type cells, discuss some of the electrical characterizations and some of the outer limits testing, and summarize the conclusions.

(Figure 2-32)

This work actually arose out of a NASA workshop on lithium batteries that was held here at Goddard last year. The purpose of this workshop was essentially to try to prioritize the efforts on lithium batteries, and at that time it was suggested that JPL carry out single work level we are describing today.

(Figure 2-33)

The type of cell was procured from the ALTUS Company, lithium thionyl chloride cell.

There is a sample of that down there where you cannot see it. Nevertheless, it has got the diameter of my column; about 60 cells were tested, they are disc-shaped much like the ones you saw earlier, just smaller size.

The rated capacity is about 6 ampere-hours, and the rest of the characteristics you can see here.

(Figure 2-34)

The next vugraph discusses some of the electrical characterization tests done on some of these materials. The objective here is to determine the voltages equivalent to the current in time in a state of charge, particularly used in the method of Shepherd. That is, to try to fit this current voltage data to this type of equation.

Indeed, the data fits these type of equations to a fair degree of accuracy. In here, you can see the actual Shepherd constants. This was done by using the constant current discharge curves.

This type of information is useful for design performance prediction.

(Figure 2-35)

This shows a plot of energy density versus power density. You can see here that you can get about 300-watt-hours per kilogram only at very low power densities with these materials. This corresponds to the order of about 30-hour rate here. However, this type of data is useful to compare with other types of cells.

There is the LeClanche cell right here. You can see the effects of temperature, 0, 21, and 40°C.

(Figure 2-36)

This shows some of the raw data that was obtained in the thermal characterization. We have voltage plotted here as well as the heat rate in watts versus time. This is the discharge curve right here. You get about 1 ampere, 21°C.

You see the heat rate in watts, how it is fairly constant. But, near the end of discharge it increases quite rapidly.

If one takes the mid-point, for example, about 30 cells. And you look at the data shown on the next vugraph.

(Figure 2-37)

Particularly, this is the heat rate plotted versus current and amperes, 21°C. The white points are the experimental data; the dark ones are the theoretical data. Based on the thermal neutral voltage of 3.34 volts, one notices that the experimental heat rates are greater than theoretical values, which suggests that some type of chemical side reaction is occurring. In particular, maybe something other than the ordinary breakdown of thionyl chloride to SO<sub>2</sub> sulfur and lithium chloride.

The other thing to notice is at the very low rates there is actually an endothermic reaction. Heat is actually absorbed down here.

(Figure 2-38)

This summarizes some of the out-of-limit tests. This is forced reversal. The actual test conditions are shown right here.

Five cells were tested at the various constant currents at room temperature, and these are 6-ampere-hour rated capacities. The results are summarized here.

No explosions, etc.; reverse voltages range from zero to -1 volt.

In this condition large negative voltage excursions were sometimes noted, and this can provide some type of problems on voltage regulation.

Venting can occur at currents greater than 0.2 amperes or about a C/30 rate. When they do vent, they do so very shortly after the onset of reversal.

(Figure 2-39)

This is some more out-of-limits tests at which they look at high rate discharge effects. This is the type of loads that we used. By way of comparison, one at 0.4-ohm load corresponds to like C/0.7 rate. This was done at room temperature again. No explosions. Surface temperatures reached about 100°C maximum during these tests. Again venting can occur whenever the rates get greater than C/0.7.

(Figure 2-40)

This really summarizes the results obtained with lithium thionyl chloride batteries from ALTUS. Shepherd constants have been determined from the EI equations. We have seen about 300 watt-hours per kilogram at very low rates.

We mentioned that experimental heat rates are larger than the theoretical rates. For rates greater than C/6, no explosions during reversal and high rate of discharge.

Again, venting is possible during reversals. A report on this work will be prepared and be available from JPL during December.

## DISCUSSION

WILLIS: Can you describe the venting and what took place?

SOMOANO: No, I can't. I don't even see that the cells have been there, personally. I can only guess that they have been up around the seals. But I have thought about that.

WILLIS: That confirms our experience. Sometimes they vent, you don't even know it.

SOMOANO: I don't know how they detect it. There is not an obvious vent port.

MAHY: All I want you to do is put your reverse voltage discharge slide back up again. I did not get to read it all.

(Figure 2-38)

Now, I want to ask the question. How far into reversal did you carry these tests? 100 percent in every case?

SOMOANO: As far as I know, yes.

CLOYD: First of all, you had 60 cells. Were they all manufactured in the same lot? And second of all, if they were in the same lot, did you find large cell-to-cell variation in these things?

Of the few that I have seen, some results have shown that there is a lot-to-lot variation with ALTUS in some areas. Some within lot variations that are tremendous.

SOMOANO: I don't know if they were from the same lot. To the best of my knowledge, they have not seen a lot of cell-to-cell variation, but I can check on that for you. But, when we talked about the material, this was not brought up. Yet I questioned it at one time. So, I don't think that there was cell-to-cell variation.

SLIWA: When these cells do vent, what are the gases that are vented, and how much?

SOMOANO: I don't know. I don't think they measure the composition of the gas or how much. That is my feeling from the test they are doing.



## AGENDA

- INTRODUCTION
- DESCRIPTION OF CELL
- ELECTRICAL CHARACTERIZATION
- THERMAL CHARACTERIZATION
- OUT OF LIMITS TESTING

Figure 2-31



## INTRODUCTION

- SPECIAL NASA LITHIUM BATTERY WORKSHOP HELD AT NASA GODDARD IN AUG 1978
- ATTENDED BY BATTERY SPECIALISTS FROM NASA CENTERS
- PRIORITIZED EFFORTS ON LITHIUM BATTERIES FOR NASA FOR FY 79
- JPL WAS REQUESTED TO CARRY OUT WORK DESCRIBED HEREIN

Figure 2-32



## DESCRIPTION OF CELLS

- TYPE - Li-SOCl<sub>2</sub>
- MANUFACTURER - ALTUS CO, PALO ALTO, CA
- MODEL NO. - AL-250
- NO. CELLS TESTED - 60
- CONFIGURATION - DISC-SHAPED
- DIMENSIONS - DIA = 6.35 cm, HT = 0.95 cm
- NOMINAL RATED CAPACITY - 6 Ah
- WT RANGE - 72-74 gms
- IMPEDANCES - RANGE: 3-15 Ω, AVG: 8 Ω
- OTHER - STAINLESS STEEL CASE (POS), CENTER POST (NEG), CERAMIC-TO-METAL SEAL

Figure 2-33

## ELECTRICAL CHARACTERIZATION SHEPHERD CONSTANTS

- GENERAL EQN:  $E = E_s - K \left( \frac{Q}{Q - it} \right) i - Ni$
- FOR AL-250 CELL:  $E = 3.5 - 0.108 \left( \frac{8.1}{8.1 - it} \right) i - 0.032i$

Figure 2-34



## ELECTRICAL CHARACTERIZATION ENERGY DENSITY VS POWER DENSITY FOR AL-250 CELLS

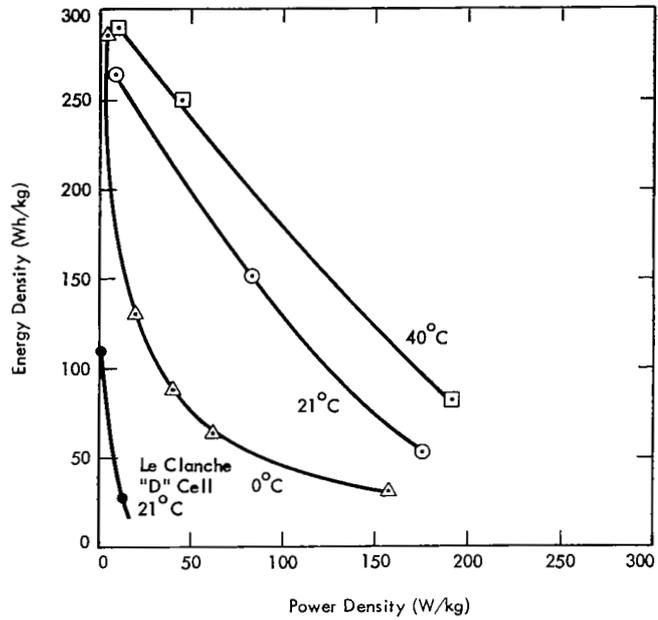


Figure 2-35



## THERMAL CHARACTERIZATION TYPICAL RESULTS OF CALORIMETRIC TESTS ON AL-250 CELLS

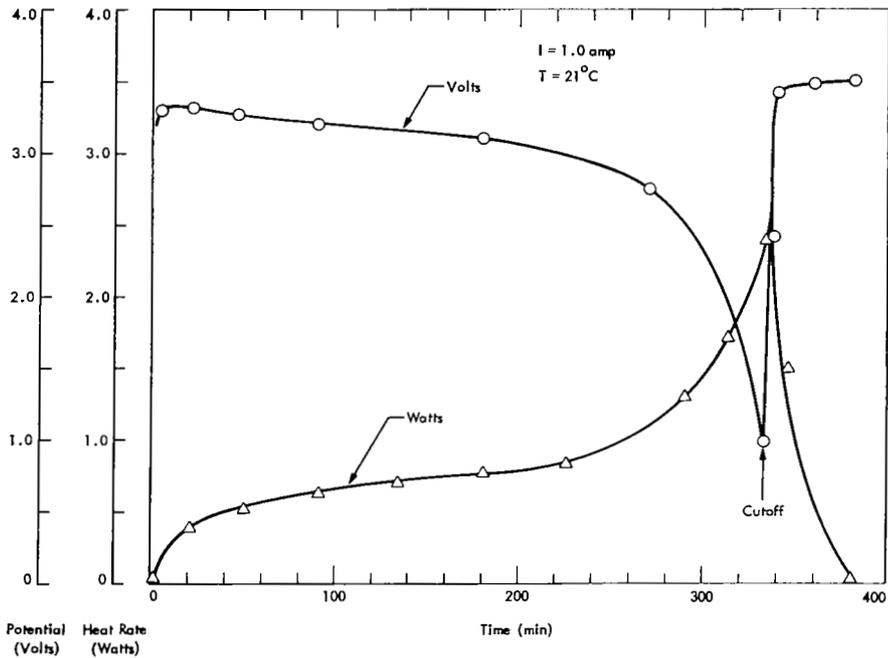
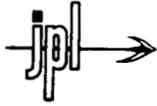


Figure 2-36



# THERMAL CHARACTERIZATION

## COMPARISON OF ACTUAL WITH THEORETICAL HEAT RATES AT MID-POINT OF DISCHARGE OF AL-250 CELLS

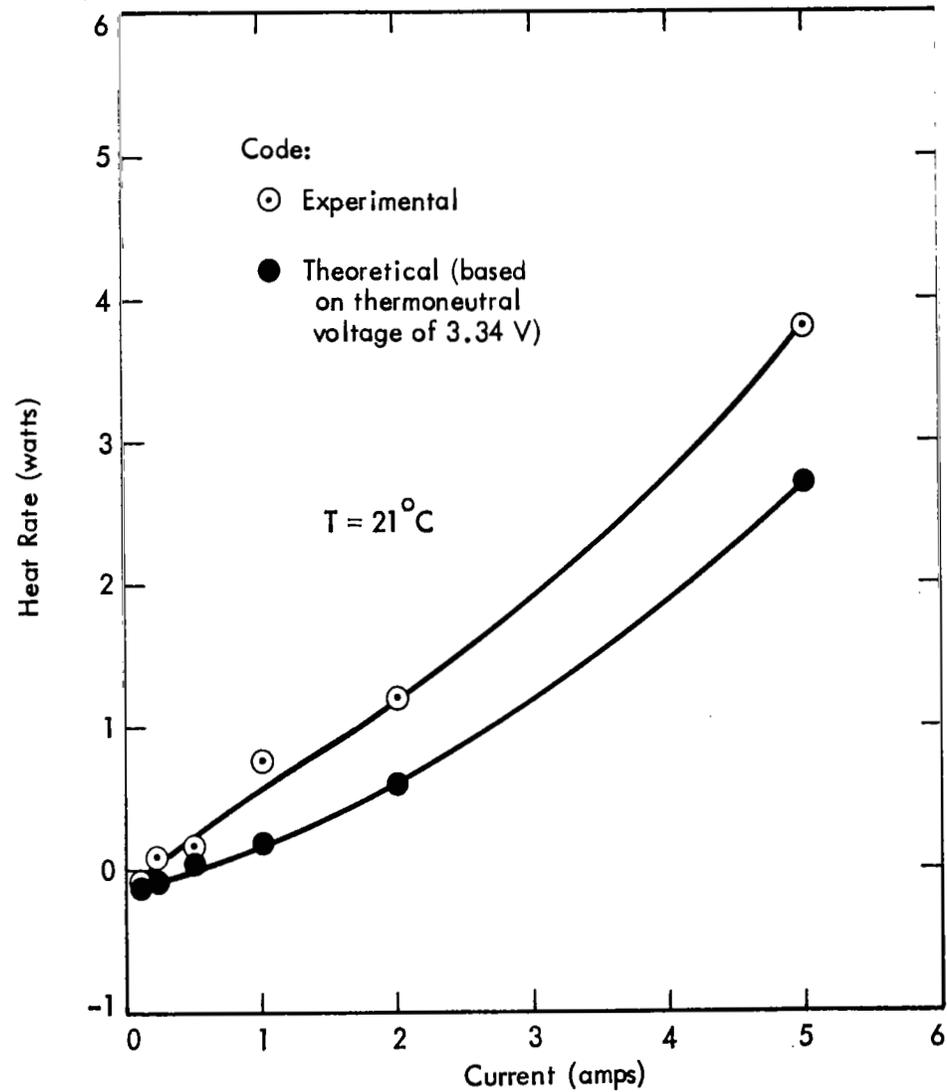


Figure 2-37



## OUT-OF-LIMITS TESTS

### FORCED REVERSAL OF AL-250 CELLS

- **TEST CONDITION:**
  - DISCHARGED, THEN REVERSED, 5 EACH CELLS AT CONSTANT CURRENTS OF 2, 1, 0.5, 0.2, AND 0.1 AMPS, RESPECTIVELY, AT ROOM TEMPERATURE FOR 100% OF RATED CAPACITY (6 Ah)
- **RESULTS:**
  - NO EXPLOSIONS
  - REVERSAL VOLTAGES USUALLY RANGED FROM 0 TO -1 VOLTS\*
  - VENTING CAN OCCUR AT CURRENTS  $> .2$  AMPS OR "C/30"
  - IF CELLS VENT, THEY DO SO SHORTLY AFTER ONSET OF REVERSAL

\*OCCASIONALLY SOME EXHIBITED LARGE NEGATIVE VOLTAGE EXCURSIONS

Figure 2-38



## OUT-OF-LIMITS TESTS

### HIGH RATE DISCHARGE OF AL-250 CELLS

- **TEST CONDITION:**
  - DISCHARGED 5 EACH CELLS ACROSS LOADS OF 0.5, 0.4, 0.3, 0.2, AND 0.1 OHMS, RESPECTIVELY, AT ROOM TEMPERATURE
- **RESULTS:**
  - NO EXPLOSIONS
  - MAXIMUM SURFACE TEMPERATURES NEAR 100°C
  - VENTING CAN OCCUR ACROSS LOADS  $< 0.4$  OHMS AND CORRESPONDING RATES  $> "C/0.7"$

Figure 2-39



## CONCLUDING REMARKS (BASED ON RESULTS OF AL-250 CELL TESTS)

- ESTABLISHED SHEPHERD CONSTANTS FOR E/I EQN
- CAN DELIVER UP TO 300 Wh/Kg AT LOW RATES
- EXPERIMENTAL HEAT RATES SOMEWHAT HIGHER THAN THEORETICAL RATES AT CURRENTS  $> "C/6"$
- NO EXPLOSIONS DURING REVERSAL AND HIGH RATE DISCHARGE
- VENTING POSSIBLE DURING REVERSAL AT CURRENTS  $> "C/30"$
- VENTING POSSIBLE DURING HIGH RATE DISCHARGE AT CURRENTS  $> "C/0.7"$
- REPORT WILL BE AVAILABLE IN DEC 79

Figure 2-40



# LITHIUM THIONYL CHLORIDE HIGH RATE DISCHARGE

K. Klinedinst  
GTE Laboratories

For the past three years, GTE has been involved in a program of research and development in the area of high rate lithium thionyl chloride power technology. This afternoon I want to quickly review the results of this for you.

(Figure 2-41)

The figure contains a listing of the four main parameters we have identified by which you can control the high-rate performance characteristics of this cell.

They include the electrolyte composition, the operating temperature, cathode design, and the cathode composition. And I am going to talk about each of these parameters one at a time, beginning with the operating temperature.

The results I am going to be showing you are obtained with experimental laboratory cells, and our purpose is to determine the range of the limits of improvement that we can obtain in high-rate performance by the variation of these parameters.

(Figure 2-42)

The next slide contains some polarization curves. This is a plot of the logarithm of the current density in milliamperes per square centimeters as a function of the cell voltage. And we are looking at 2 mil cathodes with the standard electrolyte which is a 1 1/2 molar lithium aluminum tetrachloride solution in thionyl chloride.  $\text{LiAlCl}_4$ .

We have data representing three temperatures: 25, 45, and 65 degrees. What this graph shows us is that over the entire range of current densities here, by increasing the cell temperature, the operating temperature, we realize very substantial improvements in operating voltage.

(Figure 2-43)

This next slide contains some complementary data. We are interested in the discharge capacity as a function of temperature as well, so we are plotting again on the same axis; logarithm, current density, milliamperes per square centimeter.

Now, as a function of the discharge capacity in milliamperes per hour per square centimeter. Each point here corresponds to a point in the preceding slide.

I should mention that all of this data was obtained. Each point was obtained by averaging over the discharge plateau of a separate lithium thionyl chloride cell. So, we are not looking at initial data, we are looking at data that is characteristic of the average performance of the cell.

Again, we have data for 25, 45, and 65 degrees. These curves show that again increasing the operating temperature, and we gain very substantially in discharge capacity, effectively doubling the capacity here at rates of about 20 milliamperes per square centimeter.

(Figure 2-44)

The next slide contains two typical discharge curves plotting the cell voltage as a function of the discharge time in seconds of 2 mil cathodes, again with the standard electrolyte at a rate of 100 milliamperes per square centimeter.

We have data for 25 degrees and for 65 degrees, showing the range of temperatures we covered, and I think this clearly points out the improvement in voltage and the capacity with increasing temperature.

I am going to turn now to the second of the four parameters I mentioned initially, and that is the electrolyte composition.

The standard composition, of course, as I mentioned, is the 1.5 to 1.8 molar lithium aluminum tetrachloride. We found, however, that by modifying the electrolyte by using excess amounts of aluminum chloride from one of the electrolyte constituents, we can greatly improve the high rate performance of the cell. The next slide demonstrates this.

(Figure 2-45)

We are back to polarization curves again. Logarithm current density versus cell voltage. I have data here for two electrolytes and for two temperatures covering the range of temperatures we looked at. There is the data here for the standard electrolyte at room temperature, 65 degrees, and with the excess aluminum chloride electrolyte at room temperature, 65 degrees.

I should mention the optimum performance that we found to be obtained with an electrolyte containing 4-1/2 molar aluminum chloride and thionyl chloride.

This graph shows again over the entire range of current densities and over the entire temperature range. We gained substantially in cell voltage by the use of electrolytes containing excess aluminum chloride. This seems to be true, especially true at the higher temperatures.

(Figure 2-46)

This figure contains the corresponding discharge capacity data. Again, these points correspond to the ones in the preceding slide where we are plotting the logarithm of the current density. And, now, as a function of discharge capacity, milliamperes per hour per square centimeter.

Here is the data for the standard electrolyte at room temperature, 65 degrees, and for the 4-1/2 molar aluminum chloride electrolyte at room temperature, 65 degrees.

This graph shows that not only does the use of the excess aluminum chloride electrolyte improve operating voltage, we also see very great improvement in discharge capacity resulting from the use of the excess aluminum chloride electrolyte.

(Figure 2-47)

This figure again shows two typical discharge curves plotting cell voltage as a function of time in seconds at a temperature 65 degrees and a rate of 100 milliamperes per square centimeter, fairly high rate for this cell.

We have data here for the standard 1-1/2 molar lithium aluminum tetrachloride electrolyte and for the 4-1/2 molar aluminum chloride electrolyte. Again this graph is meant to show in a practical sense here, the improvement in average voltage and the improvement in capacity associated with this parameter.

You can notice more or less this characteristic – in the beginning of the discharge curve, associated with the excess aluminum chloride. This results from the way in which the aluminum chloride interacts with one of the discharge products. And this is shown in the figure which contains the two overall reactions that occur with the two electrolytes.

(Figure 2-48)

In the case of the standard aluminum chloride electrolyte with the aluminum tetrachloride electrolytes, the lithium thionyl chloride produced sulfur and sulfur dioxide which are soluble in the electrolyte, and lithium chloride which is insoluble and which precipitates within the porous cathode.

It is the precipitation of this product within the porous cathode which is responsible for the eventual termination of the discharge reaction.

However, in the presence of the excess aluminum chloride here, aluminum chloride reacts with this product producing the soluble lithium aluminum tetrachloride and prolongs the discharge. In practice, it is the extent to which we can supply excess aluminum chloride to the cell, to the cathode which determines the discharge duration.

Now I want to turn and focus upon the cathode of the lithium thionyl chloride cell, and wonder what we can do to it to improve the high rate performance of the cell.

I listed two parameters originally: the cathode design and the cathode composition. First, we are going to talk about the design. Due to the time limitation, I am only going to talk about the simplest of design parameters. That is the cathode thickness.

(Figure 2-49)

In this figure are shown two polarization curves. Again, we are looking at log current density versus cell voltage, 25 degrees, which is standard electrolyte. The cathode thicknesses range from 2 mils to 50 mils, so we have a fairly large variation in cathode thickness.

You can see that the effect of the increased cathode thickness is not overwhelming, but it is certainly significant. It is also understandable since the electrode reduction of the thionyl chloride has occurred within the porous cathode.

So, as we increase the cathode thickness, we are increasing the internal surface area at constant geometric current density. We are therefore decreasing the specific rate of electrode reduction of thionyl chloride. So we are reducing the polarization.

(Figure 2-50)

This figure shows the effect of cathode thickness variation upon cathode utilization efficiency. Here I am plotting the cathode thickness as a function of the discharge capacity. This comes out to a unit of volume, so we are looking at cathode capacity for unit volume of cathode. This can be thought of as a method of efficiency of the cathode utilization. Again, we are at 25 degrees and at 30 milliamperes per square centimeter with the standard electrolyte.

As we decrease the cathode thickness, the efficiency of cathode utilization gradually increases until, for cathodes thinner than about 6 or 7 mils we get a more rapid increase in cathode utilization efficiency.

Why is this happening? This results because the higher the current density at which the solids discharge, the more the lithium chloride product tends to be deposited toward the side of the cathode which faces the anode.

As the lithium chloride is deposited at the entrances to the cathode pores, the interior of the cathode then becomes unavailable to support further thionyl chloride electrode reduction. So, in practice, the cathode, the higher the discharge rate, the less efficient will be the utilization of the cathode overall. Now, finally, I turn to the last of the four parameters, that of the cathode composition. The standard lithium thionyl chloride cathode is composed of a mixture of carbon black and teflon as in the case of the sulfur dioxide battery. The ratio of the materials, of course, can be varied within a considerable range. There are a great number of different carbon blacks which might be used as cathode constituents.

Of course, a great many other materials and elements are listed in the table as compounds which could be used possibly to advantage as cathode constituents. We examined a number of these, and some of the results are shown in the next figure.

(Figure 2-51)

Here I am back to the polarization curve where I am plotting the logarithm of the current density as a constant of cell voltage at room temperature, with fairly thick cathode standard electrolyte. We are looking at two different cathode compositions.

One cathode contains carbon black and teflon, and the other cathode contains an alternative cathode material. What it shows is that we can gain between 200 and 300 millivolts in operating voltage by the simple replacement of one cathode material, carbon black, with another.

(Figure 2-52)

This figure shows the corresponding discharge capacity data, the log current density as a function of discharge capacity in milliamperes per hour per square centimeter at room temperature with a 2-mil cathode standard electrolyte. The figure also shows the data for the standard and alternative cathode composition. In addition to improved operating voltage, improved cathode utilization can also result from the use of alternative cathode materials.

### DISCUSSION

BENNETT: Does the alternate cathode material also give the same type of improvement performance at higher temperatures as evidenced by the original cathode which you used?

KLINEDINST: Yes, it does.

BARNARD: As a possible user of lithium batteries, I would be more concerned with the degradation at the lower temperature, not improvement at the higher temperature. That is a pretty big degradation, really, at the lower temperature.

Do you get the same corresponding degradation in the SO<sub>2</sub> system?

KLINEDINST: I am not an expert on the SO<sub>2</sub> system. I think that question would probably be more properly addressed to someone in the audience who is. I am sure there are many of them here.

TAYLOR: The answer is, no. I think it is generally agreed that the low temperature capability of the SO<sub>2</sub> system is the best of the lithium systems to date.

VASANTH: I am interested in how far the concentration of the aluminum chloride affects the improvement of the operating conditions. Is there a limiting concentration, or do you feel it is indefinite?

KLINEDINST: The four and a half molar is the maximum that is the concentration at which the capacity optimizes and maximizes quite sharply at that concentration. You can certainly increase the concentration further. It decreases the performance.

VASANTH: My second question is, after the improvement of the operating conditions, was the solution analyzed, and was there any component operation taking place?

KLINEDINST: In general, we haven't analyzed the electrolytes.

GROSS: The addition of the aluminum chloride caused some apparent voltage delay caused by voltage overshoot. Can you explain the mechanisms that are involved in this?

KLINEDINST: Yes. Well, in the first place, there was not a voltage delay. What you were seeing was an experiment in which the electrolyte simply contained aluminum chloride. There wasn't any lithium chloride in there at all. This is a reserve-type cell in which the electrolyte is added, and then very soon the discharge is begun.

Well, if electrolyte does not have any lithium on it, then its conductivity is going to be pretty low and you will see a dip in the voltage as the electrolyte is added and the discharge is begun.

So, to answer the first part of your question: The way to get around that is to simply add a little bit of lithium chloride to the electrolyte so that the electrolyte will contain lithium tetrachloride. The reason that happens if you have pure aluminum chloride, the aluminum chloride reacts with the lithium chloride film that is on the anode and that very rapidly produces lithium tetrachloride, which is the conductive electrode salt.

Now, there is first an increase in voltage, and then it drops down. The higher voltage at first is due to really a different overall reaction. In other words, as the aluminum chloride reacts with the lithium chloride, that is as it is produced, you are not forming solid lithium chloride. So the overall reaction is different.

Then, as the aluminum chloride concentration diminishes, you start to precipitate lithium chloride and that is what causes the subsequent drop in voltage.

CLOYD: It looks very good that the actual electrolyte does include the rate capability. In certain applications, however, there is a requirement of the intermittent stop of the current flow.

What is the wetstand capability of that lithium system in the electrolyte like that? Obviously, it gives off protons. Is it at a very fast rate, or what?

KLINEDINST: Of course, it would be temperature dependent. But, I would say that the use of an electrolyte like that would pretty much be limited to a reserve battery configuration in which you do not have long periods of open circuit stand, or low rate discharge involved. The reaction of the aluminum chloride with the lithium anode would prohibit long periods of stand.

# **Li / SOCL<sub>2</sub> CELL DESIGN PARAMETERS**

- **ELECTROLYTE COMPOSITION**
- **OPERATING TEMPERATURE**
- **CATHODE DESIGN**
- **CATHODE COMPOSITION**

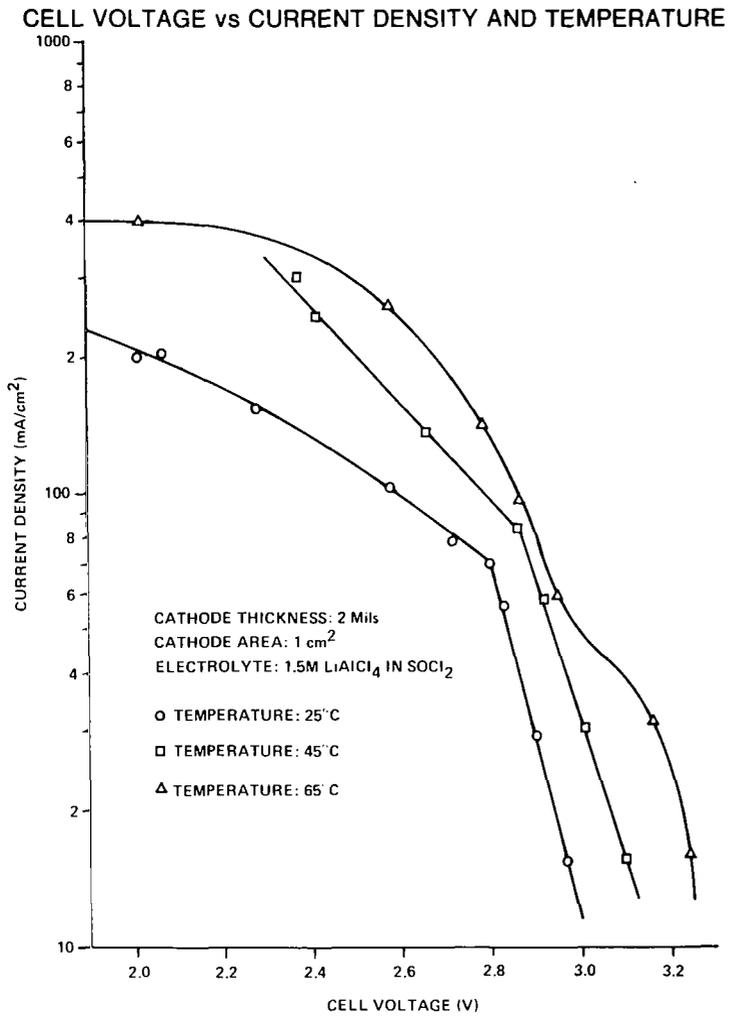


Figure 2-42

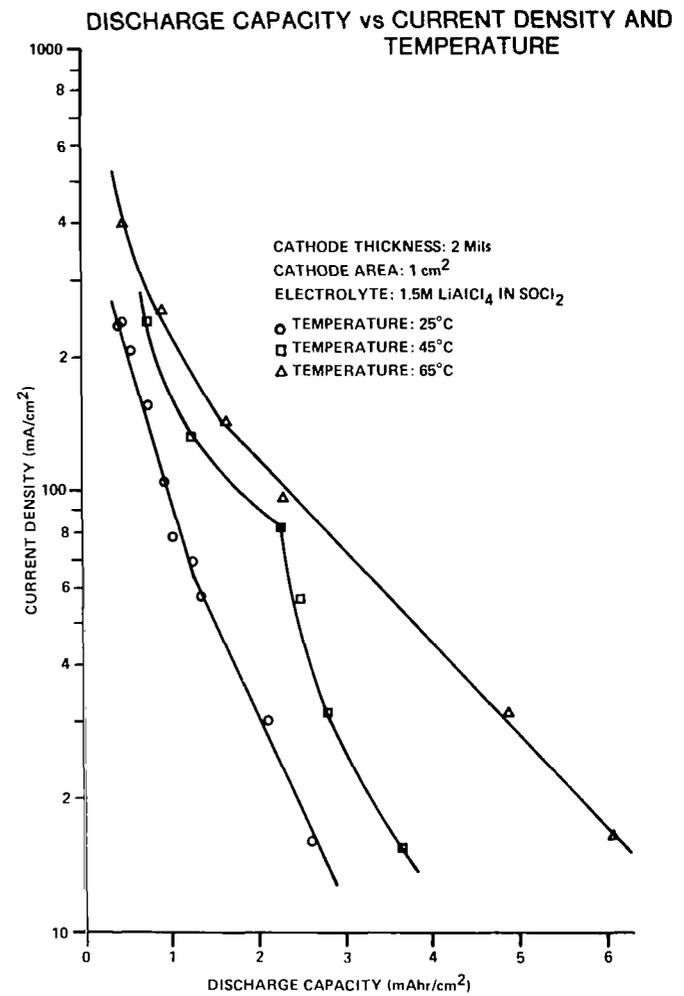


Figure 2-43

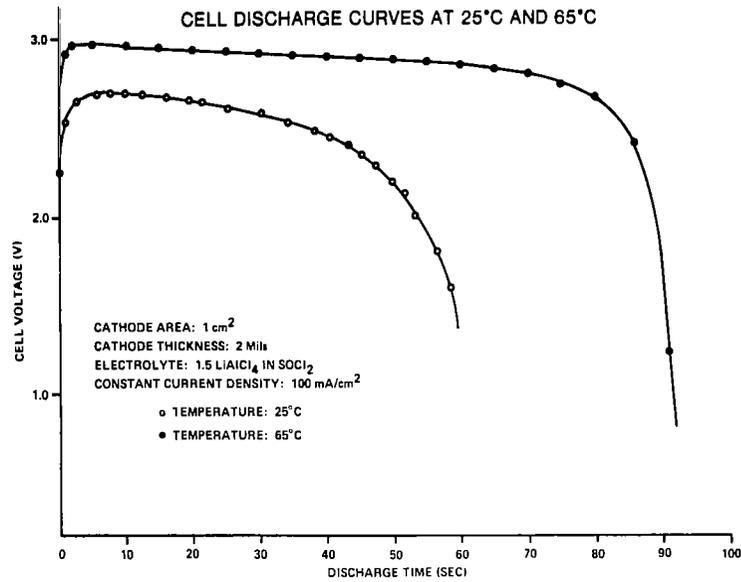


Figure 2-44

**CELL VOLTAGE vs CURRENT DENSITY AND TEMPERATURE  
 USING  $1.5 \text{ M LiAlCl}_4$  AND  $4.5 \text{ M AlCl}_3$  IN  $\text{SOCl}_2$  AS  
 ELECTROLYTE SOLUTIONS**

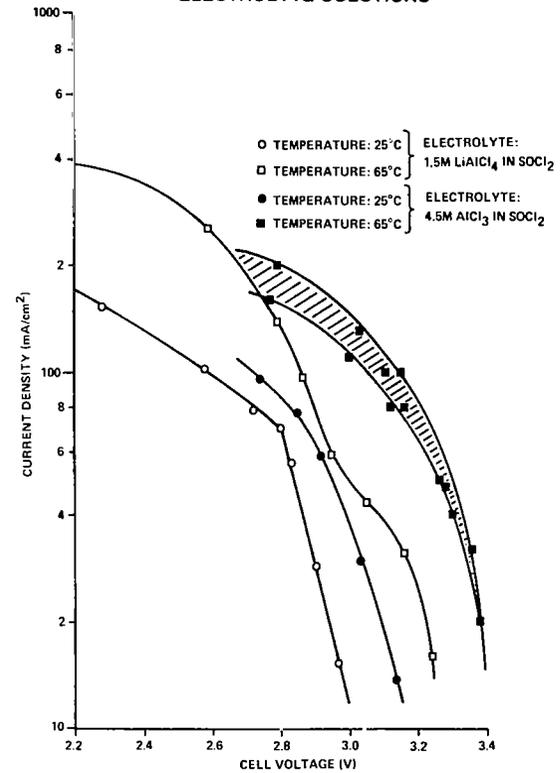


Figure 2-45

DISCHARGE CAPACITY vs CURRENT DENSITY AND TEMPERATURE USING 1.5M LiAlCl<sub>4</sub> AND 4.5M AlCl<sub>3</sub> IN SOCl<sub>2</sub> AS ELECTROLYTE SOLUTIONS

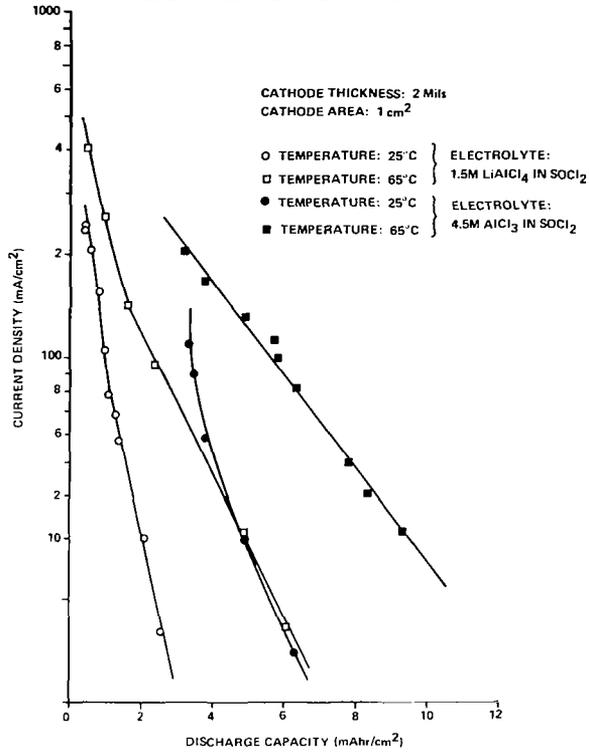


Figure 2-46

CELL DISCHARGE CURVES AT 65°C USING 1.5M LiAlCl<sub>4</sub> AND 4.5M AlCl<sub>3</sub> IN SOCl<sub>2</sub> AS ELECTROLYTE SOLUTIONS

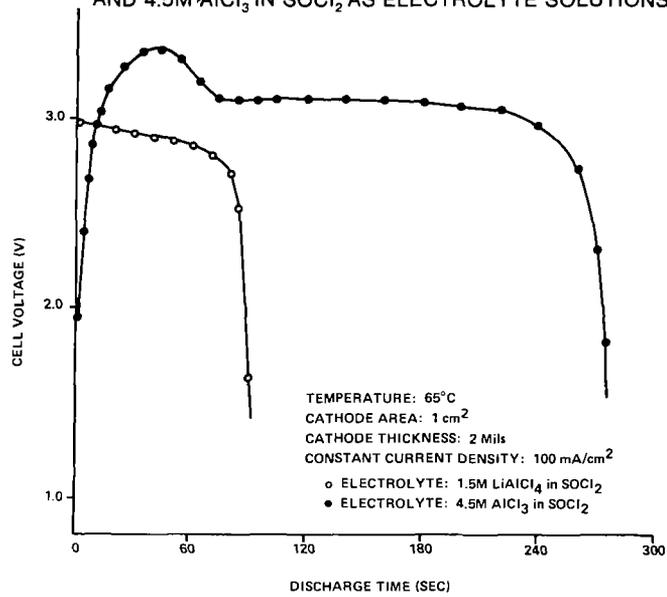
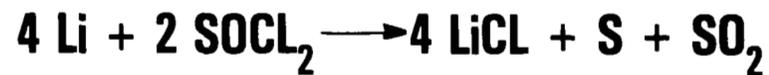


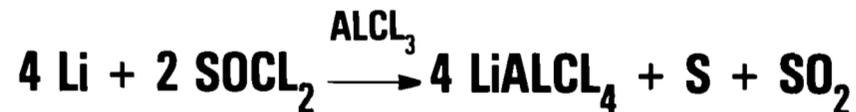
Figure 2-47

# Li / SOCL<sub>2</sub> CELL DISCHARGE REACTIONS

WITH LiALCL<sub>4</sub> ELECTROLYTE



WITH ALCL<sub>3</sub> ELECTROLYTE



CELL VOLTAGE vs CURRENT DENSITY AND CATHODE THICKNESS

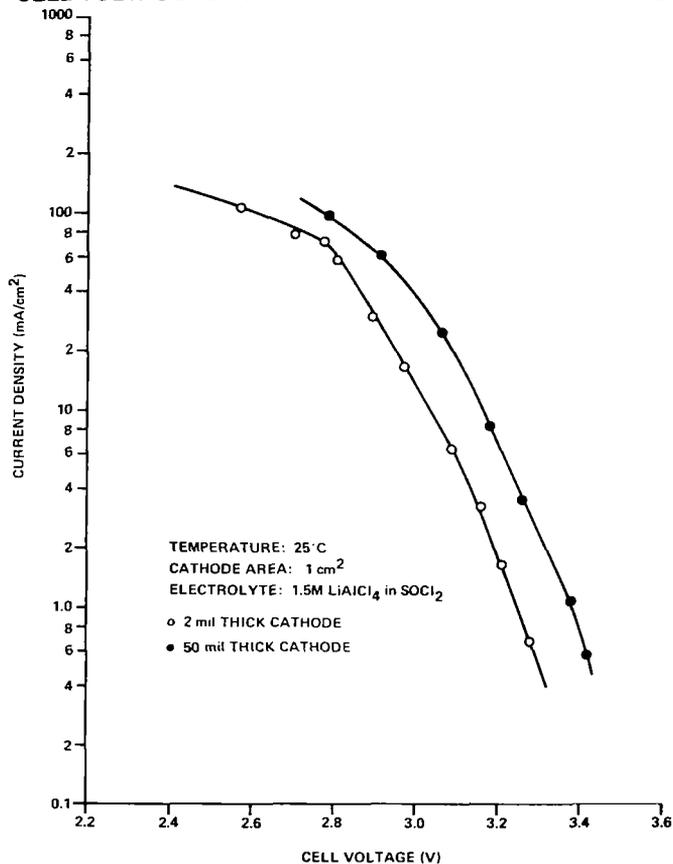


Figure 2-49

CATHODE UTILIZATION vs CATHODE THICKNESS

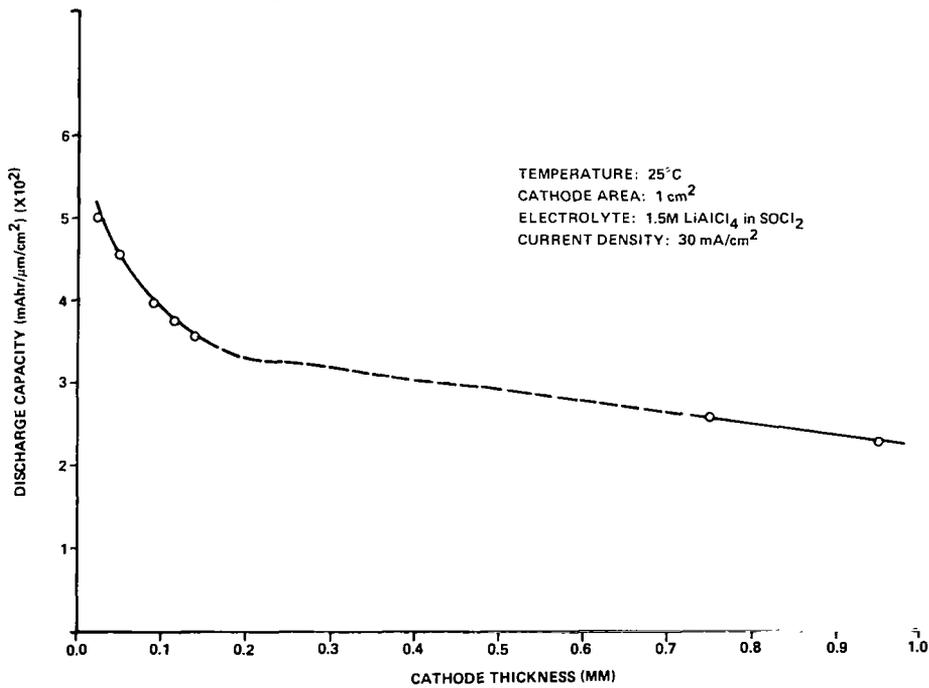


Figure 2-50

CELL VOLTAGE vs CURRENT DENSITY WITH STANDARD AND ALTERNATIVE CATHODE MATERIALS

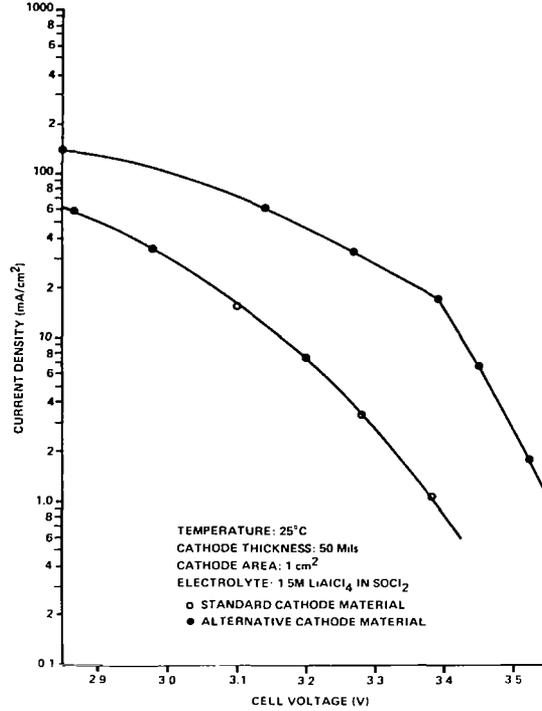


Figure 2-51

DISCHARGE CAPACITY vs CURRENT DENSITY WITH STANDARD AND ALTERNATIVE CATHODE MATERIALS

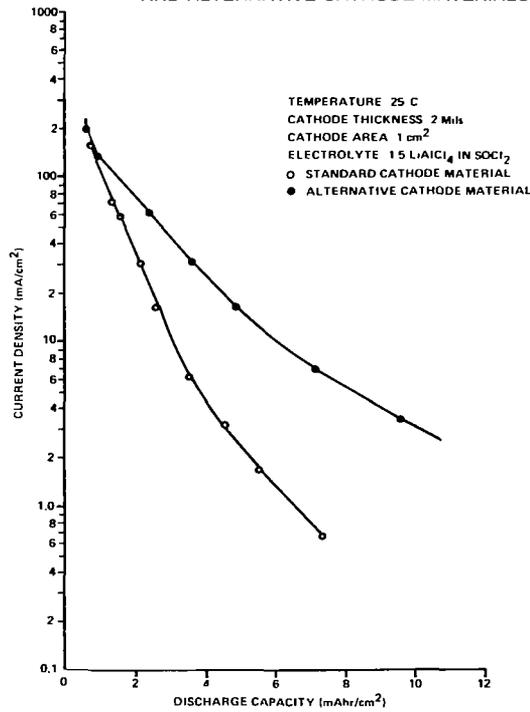


Figure 2-52



## LITHIUM BATTERY DISCHARGE TESTS

C. Johnson  
Boeing

I would like to report today on the preliminary results of the lithium cell discharge tests that we have been conducting at the Boeing Company for about the past year.

These results are preliminary in that the test is ongoing and it will continue for several years into the future. But, they are indicating some interesting things, and we wanted to present the data that is presently available.

The test is different from most discharge tests in that it is extremely low rate. What we are looking for is long-term applications for lithium cells.

(Figure 2-53)

The objective of the test is to characterize the long-term discharge of a vast variety of lithium cells that are currently available and to test the susceptibility that cells have to chemical variation during the very slow discharge.

We know the lithium electrode is extremely active, and chemical reactions will tend to parasitize or to rob the lithium from the reaction we would like to produce, the electrochemical generation of energy. The technical approach that we are taking is to detect this chemical degradation by using the extremely long-term testing.

What we are doing is measuring the voltage as a function of time; what we are looking for are to see preliminary failures that occur as evidenced by the drop in voltage prematurely to the expected cell life.

Basically what we are doing is to set a very small shunt resistor, or a very large shunt resistor, across the cell terminals and to monitor the voltage as a period of time. We calculate the resistance value such that the cell will be drained in the specific time period. The times that we are testing are 1/4, 1/2, 1 year, 2 years, 4 years, 8 years, and even 16 years of discharge.

Now, of course, the question that immediately comes to mind is, who wants to wait around for 16 years for the test results? Our answer to that is that we don't plan to wait 16 years. We are hoping to find those systems that will be able to withstand the chemical degradation, to maintain their voltage during that time, and to eliminate those systems that show problem areas during the voltage discharge.

The hypothesis that is being tested is that the lithium electrode is very active. One reason that it does not chemically react is that it forms a passivating layer on the lithium surface.

What we are doing during the low-discharge rate is maintaining an active lithium electrode. We are assuming that the chemical degradation reactions will be more prevalent during this active time of the electrode.

So, what I would like to show next is the vast number of systems that we have in test at this time.

(Figure 2-54)

As you can see, there are more systems than these available now. But these are the systems that we have tested: the lithium carbon monofluoride, lithium copper oxide, lithium iodide, lithium iron, sulfide, the lead iodide system and manganese dioxide, and the silver chromate. Two that have been reported on quite a bit today are the lithium sulfur dioxide and the thionyl chloride system. We also had some cells from the vanadium pentoxide.

I have listed the chemical designations and used several abbreviations as I have enumerated at the bottom of this figure.

(Figure 2-55)

The kind of results that we are getting is a lithium carbon monofluoride system that has been discharged at a rate of a force of a year. As you can see, the voltage maintains its value to the calculated cell life. This cell, we would expect, has met the criteria of the test and does not show appreciable chemical degradation during slow rate discharge.

(Figure 2-56)

The lithium copper oxide system at a 1-year rate has shown some premature failure, although it is not very severe. The cell voltage did drop off before the calculated cell life was attained.

(Figure 2-57)

Another cell which was being discharged at a 2-year rate has already failed at less than 40 weeks, and the cell voltage fluctuated slightly, showing these voltage fluctuations and then premature failure as the voltage dropped off at a time much less than the calculated cell life.

(Figure 2-58)

Another system, the lithium iron sulfide system, shows to be very promising.

(Figure 2-59)

During the 1/2-year rate shown here, two cells essentially met the calculated cell life, and another cell which was discharged at another rate also met the calculated cell life. Perhaps the longer timeframe will show up some additional results. But this is what we have at this point.

(Figure 2-60)

The manganese dioxide system looks to be fairly favorable at a 1/4-year rate. The cell has discharged a little bit prematurely, but has essentially met the requirement.

(Figure 2-61)

As we increase the time or decrease the rate at which we are discharging, we find that one of two cells in this slide has experienced some premature failure, and the voltage has dropped off prematurely. The other cell seems to have met the requirement.

(Figure 2-62)

We have another cell which we are discharging at a 1-year rate, and it is also showing premature failure in dropping off in cell voltage.

(Figure 2-63)

This is the lithium sulfur dioxide system that we have tested. These are actually three cells plotted on the same chart. You can see two of the cells have lost their voltage prematurely, whereas one of the cells came very close to meeting the expected or calculated cell life. These were discharged at a 1/2-year rate.

(Figure 2-64)

Similar cells discharged at a 1-year rate show much the same phenomena with all the cells discharging prematurely.

(Figure 2-65)

We have two cells being discharged at a 2-year rate, and already one of the two cells has experienced premature failure. The other cell is continuing in voltage. We are looking to see when it might lose its voltage also.

**VOICE:** Are these at room temperature?

**JOHNSON:** Yes, they are at room temperature.

(Figure 2-66)

The lithium thionyl chloride system is being discharged at a 1/2-year rate; two cells are showing discharge prior to the calculated cell life, but very close to meeting the expected cell life.

(Figure 2-67)

At our 1-year rate, we see that the voltage dropped off a little bit more prematurely than the previous figure showed. We have to wait to see what the 2-and 4-year rates will show on this system.

(Figure 2-68)

The lithium vanadium pentoxide system shows a characteristic two-step voltage discharge, discharging first at about 3.3 volts and then dropping down to second plateau. This second plateau would be expected to reach the calculated cell life, although we experience a premature failure and the voltage drops off prematurely.

Well, it is still early in the test to come to any definite conclusions. But, the results are indicating that several of the lithium cell systems may be susceptible to chemical degradation over a long period of time. And this, of course, decreases the expected cell life.

The conclusion that can be made is that the test does show some promise as a useful criterion of measuring those systems which are susceptible to chemical degradation. Or perhaps, more importantly, it would be those systems that are not susceptible to the chemical degradation.

The future work we have planned is that during 1980, we plan to add additional systems to the tests and to fill out the test matrix to include three specimens ourselves for each discharge timeframe.

Also, we would like to add some control specimens which we plan to leave at open circuit voltage to monitor their voltage during the same time period.

## DISCUSSION

BIS: Are these all research cells, or are these commercially available cells?

JOHNSON: These are essentially commercially available cells that we have in test, yes.

BIS: Could you identify some of the more prominent ones like thionyl chloride and the SO<sub>2</sub>? Who the manufacturers were?

JOHNSON: At this point, we have cells from most of the major manufacturers. I don't think it is fair to specifically identify specific manufacturers because, first of all, the test is an ongoing

st, and the results are preliminary at this stage. We are not in the business to critique manufacturers.

BENNETT: Can you tell me whether or not all these cells are being discharged in the same orientation, and what orientation is that?

JOHNSON: I would say that the cells are being discharged in a vertical orientation. Does that answer your question?

BENNETT: The header part of the cell was in the upright position then?

JOHNSON: Most of them are C cells or D cells, and they are laying . . .

BENNETT: On their side?

JOHNSON: Yes.

THORNELL: Do you do any storage weight measurements on these long discharges?

JOHNSON: No, we haven't done any weight measurements during discharge.

MALACHESKY: You made a point that you are looking at chemical degradation. Is it possible some of these premature failures that you see are, in fact, due to the failure with the krebs meals that are on these calls? Have you looked for a visible salt encrustation? For example, in the manganese dioxide cells?

JOHNSON: We do examine the cells after they are discharged, and we have not seen any specific problems on that particular system or other systems.

VASANTH: I would like to know whether chemical analyses are done after the discharges are connected? And whether you find any difference from one to the other?

Of course, there should be a difference because you have been studying a various number of cells. Can you throw some light on this aspect?

JOHNSON: We have not dissected any cells at this point. We plan to do some of that in the future. We are planning an expanded test in 1980, and during that test, we do plan to examine cells as they discharge.

VASANTH: At this point, can you say what practices are responsible for the degradation of these cells? Any idea?

JOHNSON: I think there is a variety of systems being tested, and in each one of the systems the degradation process could be slightly different.

Our hypothesis is that we are looking mostly at the lithium electrodes side of the system. But, there have been many indications today that the cathode side of the system is also important. So we are still open on that point.

FELDHAKKE: The data you presented, is that typical data, or is that actually the number of cells that you have under test, two or three in the various types?

JOHNSON: Yes. We have, in many cases, one, two, or three cells being tested of a specific type. When there are several manufacturers of the same cell, then we have additional cells. But, the slides that I showed today were of a specific type.

FELDHAKKE: So you may have tested only two or three cells in some cases.

JOHNSON: Yes, that is correct.

We plan to expand that in this next test and make sure that we have three in each case, plus an additional control test. So there would be four.

TAYLOR: I am going to take this point up again. Did I understand you correctly to say that the results you are getting are representative of all manufacturers for these different systems?

JOHNSON: I may have used the word "slightly" there.

TAYLOR: You have given a series of systems there. And let's face it, SO<sub>2</sub> is one of them. I think that you said also the SO<sub>2</sub>s that you were talking about double A-size cells, for example?

JOHNSON: Yes.

TAYLOR: Are you telling me that that is representative of the SO<sub>2</sub> cells made by a group of manufacturers? All of the SO<sub>2</sub> system manufacturers?

JOHNSON: I didn't mean to indicate that, no. We feel that these are preliminary results, and we are going to add to the tests in 1980 to include a lot more manufacturers and more systems. At this point several of the systems involved only one vendor, or maybe two or three.

TAYLOR: I am happy to hear you say that for obvious reasons. I really do think that the conditions you have are, in fact, very benign, room temperature discharge. I am absolutely amazed to see the falloff in performance — you got two out of those three cells.

I do know and have published data, for example, on hermetic cells, which have undergone a charge-up of 1.2-year rate continuous attempts, up to +60°C, without any failures.

Standing that against room temperature over 6 months?

JOHNSON: Some of the data is 1 year. But, yes, we were surprised to see some of the discharges that did occur.

TAYLOR: The point I am making is that I don't think it is really realistic to draw conclusions on that data yet.

JOHNSON: The conclusion I was trying to draw is that the test is worthwhile and we should continue it.

METHLIE: Mr. Johnson, I would suggest that perhaps in each case you could go back to the designer of the cell and ask him for the conditions you were looking at, what the minimum-maximum-medium performance might look at and see how you would rate the groups within that.

## LITHIUM-CELL DISCHARGE TEST

### OBJECTIVES

- TEST LONG-TERM DISCHARGE CHARACTERISTICS
- EVALUATE VULNERABILITY TO CHEMICAL DEGRADATION

### TECHNICAL APPROACH

- DETECT CHEMICAL DEGRADATION BY LONG-TERM TESTING
- EXAMINE VOLTAGE VS. TIME BEHAVIOR DURING DISCHARGE
- INVESTIGATE PREMATURE FAILURES

Figure 2-53

TABLE 1  
LITHIUM CELLS IN TEST

LITHIUM/CARBON MONOFLUORIDE	Li/LiBF <sub>4</sub> , BL, DME, PC/(CF) <sub>n</sub>
LITHIUM/COPPER OXIDE	Li/LiClO <sub>4</sub> , SOLVENT/CuO
LITHIUM/IODINE	Li/LiI/I <sub>2</sub> -P2VP
LITHIUM/IRON SULFIDE	Li/FeS
LITHIUM/LEAD IODIDE	Li/LiI(AI <sub>2</sub> O <sub>3</sub> )/PbI <sub>2</sub> , PbS
LITHIUM/MANGANESE DIOXIDE	Li/LiClO <sub>4</sub> &LiBF <sub>4</sub> , DME&PC/MnO <sub>2</sub>
LITHIUM/SILVER CHROMATE	Li/LiClO <sub>4</sub> , PC/Ag <sub>2</sub> CrO <sub>4</sub>
LITHIUM/SULFUR DIOXIDE	Li/LiBr, AN&PC/SO <sub>2</sub> at Carbon
LITHIUM/THIONYL CHLORIDE	Li/LiAlCl <sub>4</sub> , SOCl <sub>2</sub> /SOCl <sub>2</sub> at Carbon
LITHIUM/VANADIUM PENTOXIDE	Li/LiAsF <sub>6</sub> &LiBF <sub>4</sub> , MF/V <sub>2</sub> O <sub>5</sub> at Carbon

AN = Acetonitrile  
 BL =  $\gamma$ -Butyrolactone  
 DME = Di-Methoxyethane  
 MF = Methyl Formate  
 PC = Propylene Carbonate  
 P2VP = Poly(2-Vinylpyridine)

Figure 2-54

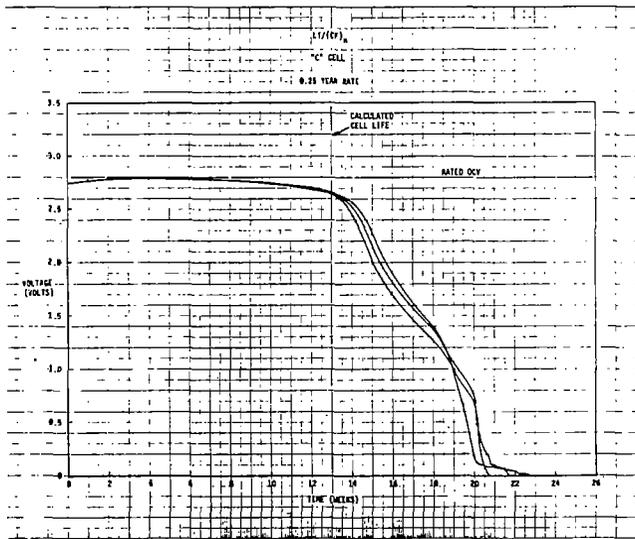


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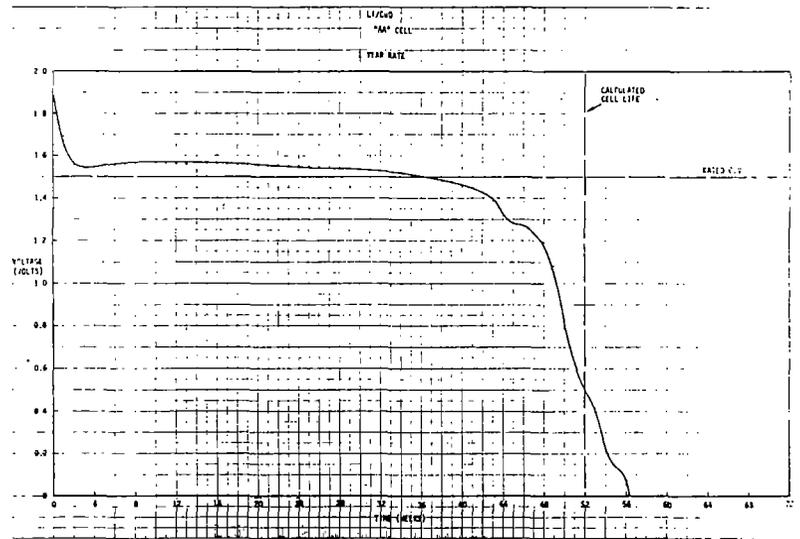


Figure 2-56

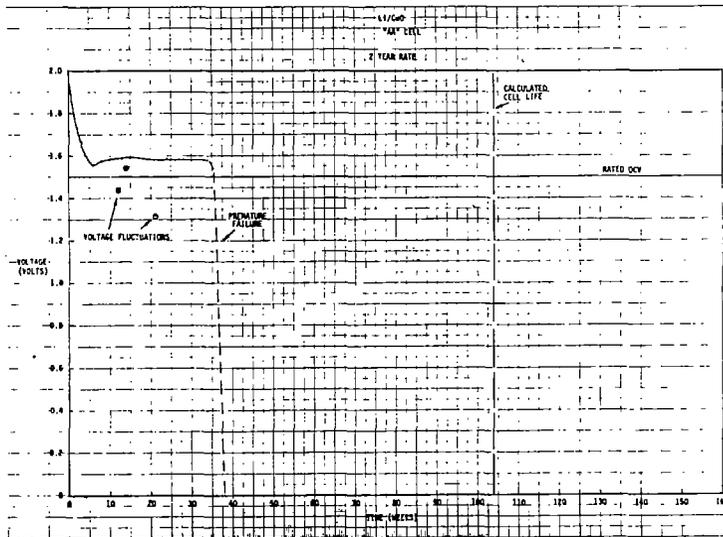


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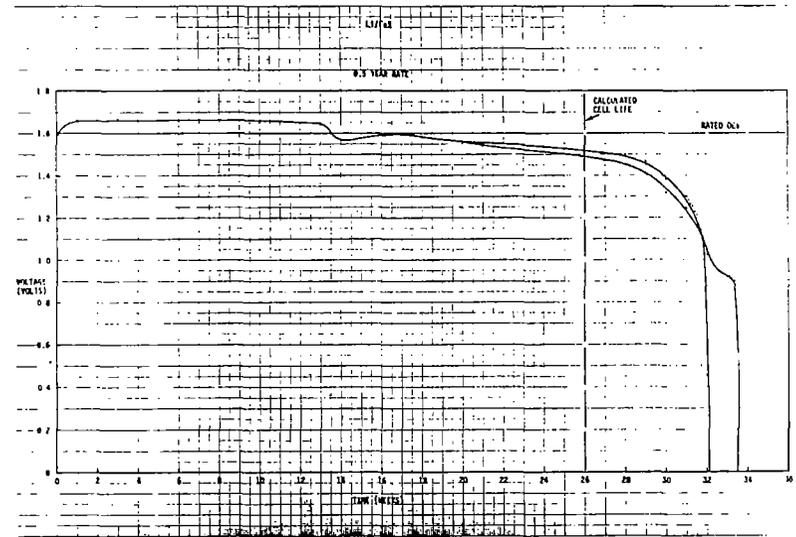


Figure 2-58

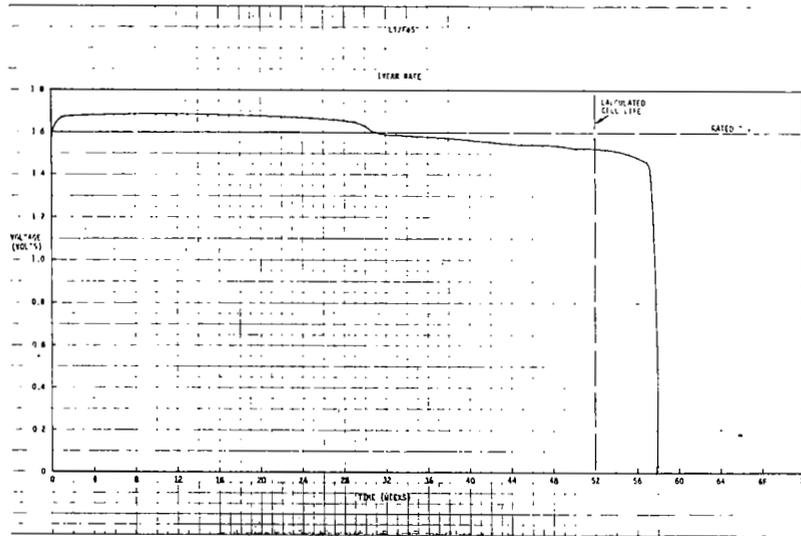


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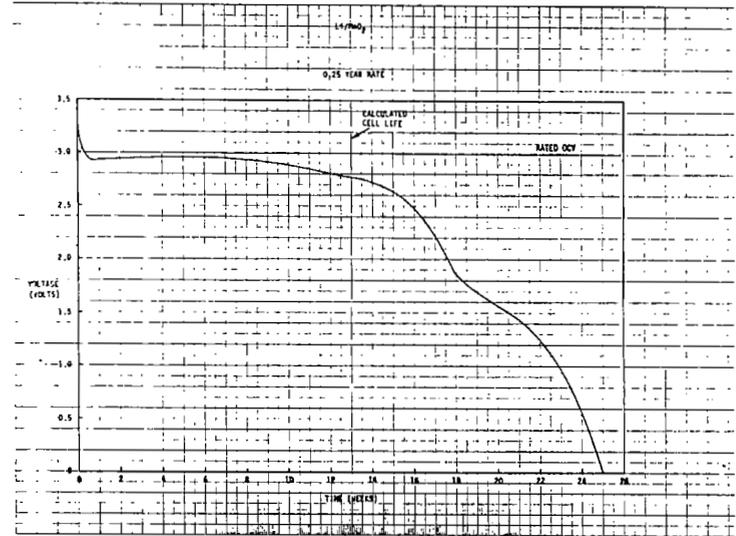


Figure 2-60

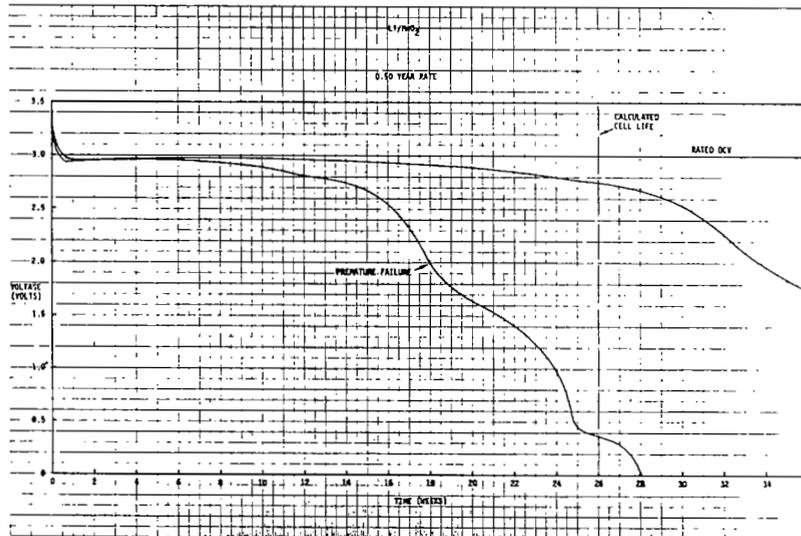


Figure 2-61

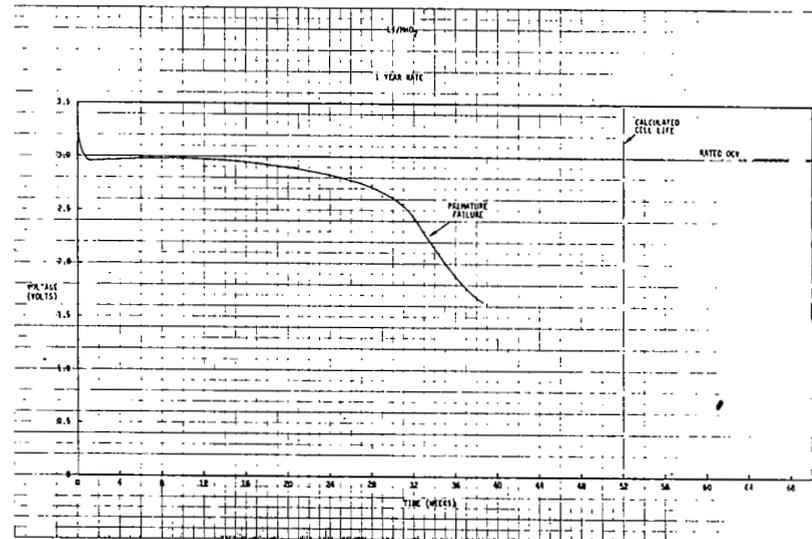


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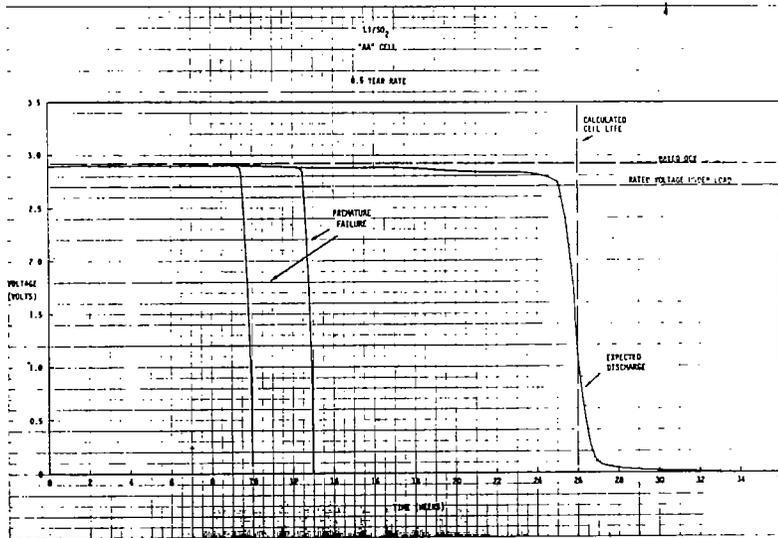


Figure 2-63

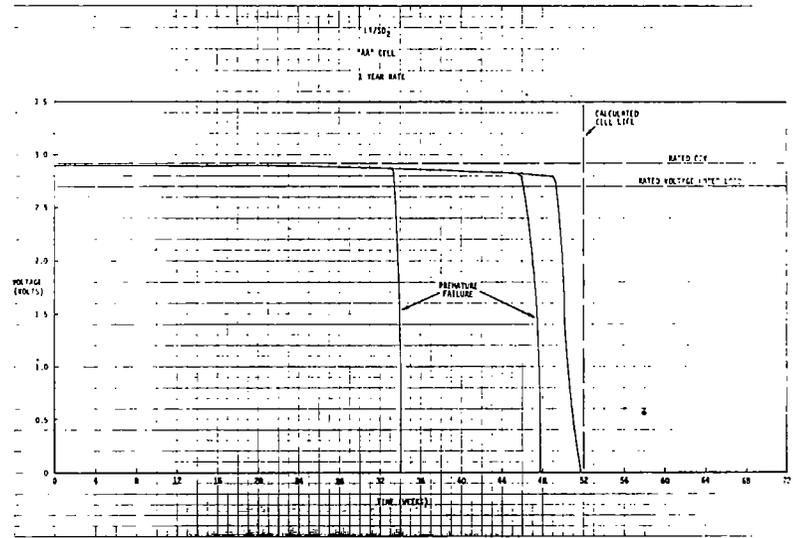


Figure 2-64

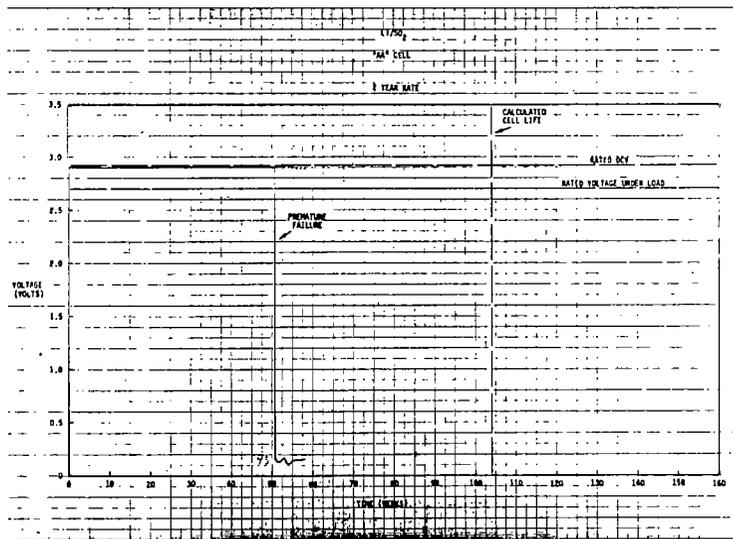


Figure 2-65

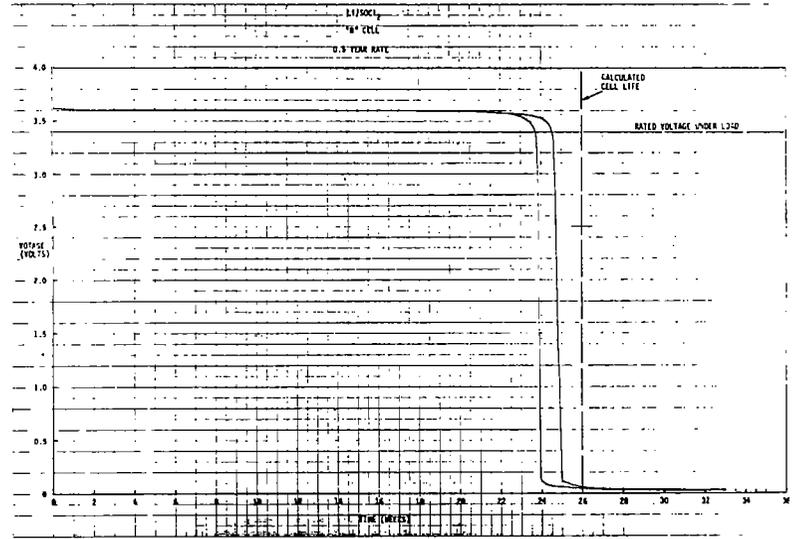


Figure 2-66

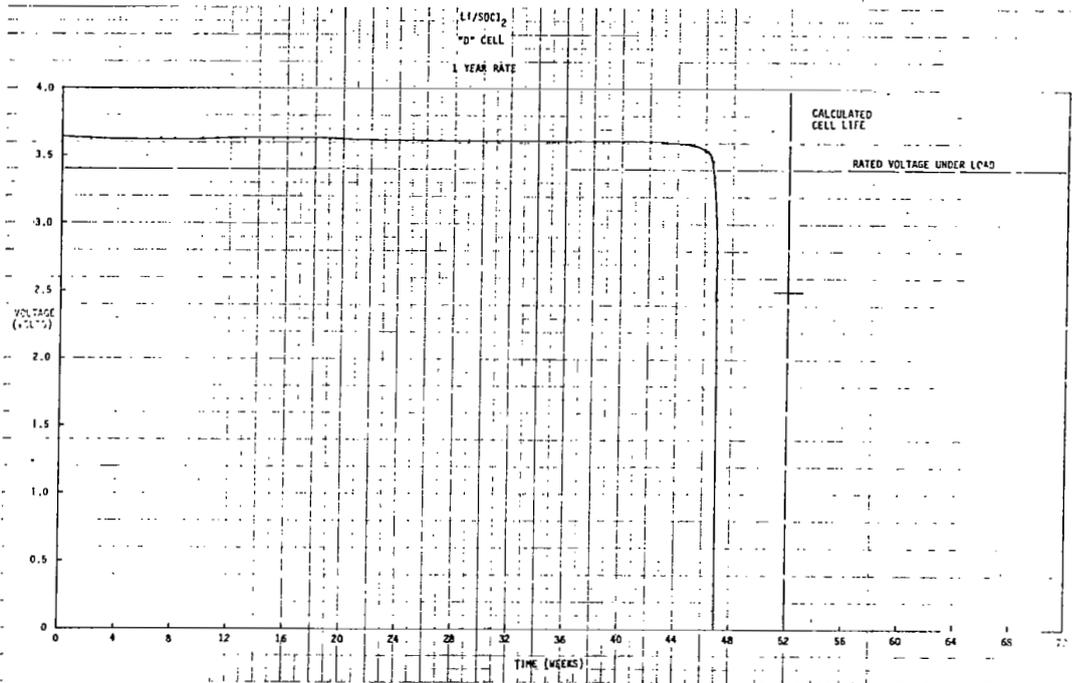


Figure 2-67

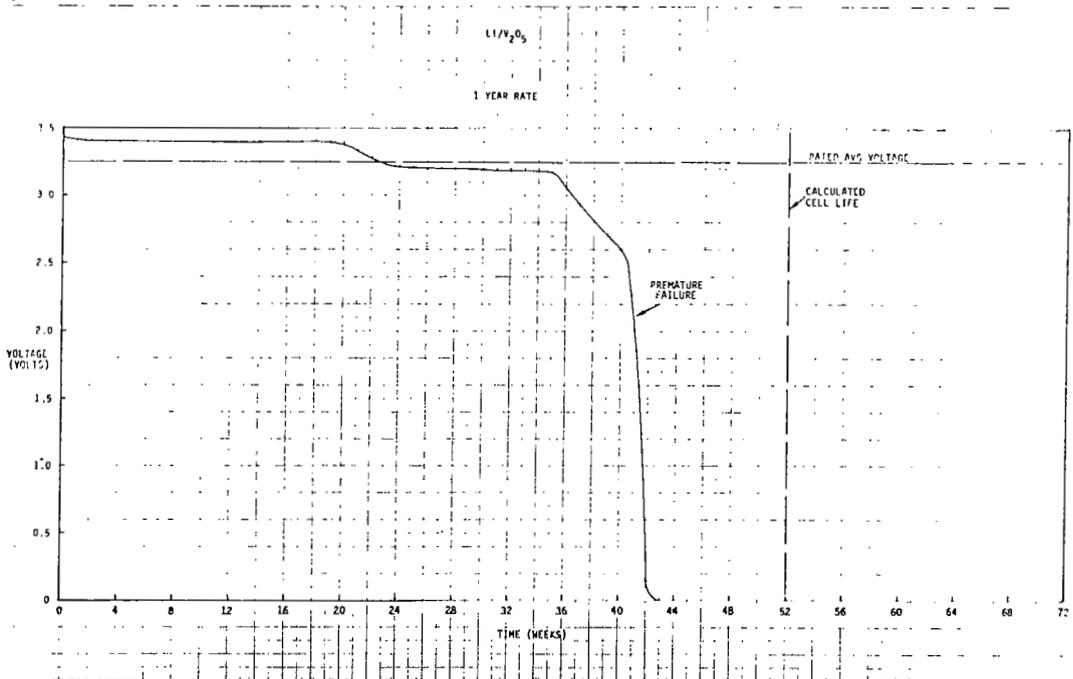


Figure 2-68

## CHARACTERIZATION OF PROTOTYPE SECONDARY LITHIUM BATTERY

R. Somoano  
JPL

I would like to discuss some of the work that is going on at JPL as a result of a new NASA-sponsored program which has recently been initiated on ambient temperature secondary lithium batteries.

(Figure 2-69)

The objective of the program is to develop improved ambient temperature lithium batteries from cells which would satisfy NASA's needs for energy density, safety, cycle life, etc.

By way of example, we are interested in energy densities of the order of 150 watts per kilogram or higher; cycle life of 200 to 500 cycles, or greater; make certain that life of battery is safe as possible, 5-to 10-year lifetime. These are the type of things we are checking for.

(Figure 2-70)

The type of system secondary lithium batteries that we are working on involves the use of an intercalatable cathode. These are based on the layered transition metal chalcogenides, such as titanium disulfide. You will be hearing some more of these talks following this one.

TiS<sub>2</sub> is much like graphite in that it crystallizes in layers, and the layers have been held together very weakly by van der Waals forces. One can make a battery out of this material with the lithium anode, suitable electrolyte and this layered structure as the cathode. Upon discharge, lithium ions can diffuse between the layers. The layers will open up and accept the lithium ions, and upon charge, the lithium can be removed back out with very little destruction and change of structure.

Indeed, one can do this over and over, and this is what one tries to exploit as a reversible cathode, which has an energy density of around 450 watt-hours per kilogram.

(Figure 2-71)

Well, the organization of the task here at JPL involved efforts focused on all components of the cell, anode, electrolyte, and cathode. This program is primarily a basic research program. That is, we are interested in gaining an understanding of the fundamental processes which can dominate and which can limit battery performance.

One aspect of this program is also a battery testing and evaluation. This reflects the fact that in a few years the basic research effort will tool down and be replaced by a prototype cell effort, in which they will be fabricating prototype cells in JPL for evaluation.

Prior to the initiation of this program in July, some cells have been purchased. Prototype cells have been purchased to evaluate at JPL. What I would like to do now is just discuss with you some of the very preliminary data, very preliminary in that I shall say we have tested three cells so far.

I think it will be interesting to you to be able to see the data we have obtained and to compare with some of the data you will hear in the next few talks.

(Figure 2-72)

So, as far as the evaluation of a prototype cell is concerned, what we are interested in is to try to find out just what would be the performance of a cell that we could go out and buy state-of-the-art cell, just to get a feeling of what type of performance characteristics one could expect. We wanted to identify the problem areas to see if there were any immediate near-term development needs and to make sure that these are being addressed by the basic research program as well.

The approach here was to go to a vendor – in this case, EIC in Newton, Massachusetts, and have him fabricate some lithium  $\text{TiS}_2$  type cells for us. A typical type cell is shown right here. It is a prismatic cell.

EIC actually made two types of cells for us, D cells as well as prismatic cells. The D cells, we were alerted by EIC, had a contamination problem in which impurities ostensibly water in the  $\text{TiS}_2$  cathode could possibly contaminate it, contaminating the lithium anode, and therefore lead to capacity fading.

The prismatic cells were made under much better conditions and were thought to be superior cells. These are hermetically sealed cells. We have essentially tested two of the D cells as well as one of the prismatic cells.

Since these are the first secondary lithium batteries that have been tested at JPL, the tests were done in their remote testing facility. What this results in is that we can only test a cell at a time so it is really quite slow.

So I will be showing you the results of testing two D cells and one prismatic cell. This work is currently in process and will be continuing.

(Figures 2-73)

The first vugraph right here shows a discharge curve for lithium  $\text{TiS}_2$  cell. I should mention that the electrolyte in this material consists of a salt, lithium arsenate hexafluoride. The salt was 2

methyl KHF. These are ostensibly supposed to be about 5-ampere-hour capacity levels. That was one of the desired characteristics.

This is a discharge curve for a lithium  $\text{TiS}_2$  cell. Notice that the discharge curve is about 300 milliamperes, so it is really quite low. But, indeed, that is what was used for the testing procedures.

JPL, as well as NASA, is certainly interested in higher discharge rates for the secondary lithium batteries, in particular C/1, C/1.5 type rates. But, initially to characterize this material, we used a 300-milliampere rate which is about the order of C/11.

If you look at these results, it corresponds to a capacity of about 3.4 ampere-hours if you use an average voltage of around 2 volts. You see it is about 57 watt-hours per kilogram in this particular cell. This is the first cycle, the first discharge.

We have done some ID characteristics down near the fully discharged region, as shown in the next vugraph.

(Figure 2-74)

This is the voltage versus current. As you can see, from the right is discharge; from the left is charge.

Nothing really unusual is seen here. It is a typical behavior that we expect. This indicates there is no other type of adverse reaction occurring, at least within the current voltage range that we have been looking at.

(Figure 2-75)

On the next vugraph we will show you a typical charge cycle. Again, it is used at 300 milliamperes. A couple of features I would like to point out here. It is quite similar to the discharge curve. It is a little higher voltage. But, you will notice a sharp upturn near the fully charged state.

We don't know what is causing it to turn up like that. It is something that can be used as control point possibly. We have terminated the test at 3 volts as well as 1.6 volts, and these are the recommended cutoff voltages as suggested by EIC.

We have done some IV characteristic tests right near the fully charged region, which is shown on the next vugraph.

(Figure 2-76)

They are really quite different from the fully discharged state. Again, for discharge situation, there is not much change, but as you notice when we charge, especially above 3 volts, there is quite

high voltages being generated. We don't really know what is the cause of it. It has been suggested to us by EIC that what may be happening is electrolyte degradation here, in particular polymerization reaction. In any event, this is one of the areas we will be interested in to see what is happening in these regions.

(Figure 2-77)

The next vugraph shows load capacity versus cycles. I would like to call your attention to the solid line first. Again, this is the first D cell tested. You see roughly about 3-ampere-hours capacity to about the 15th cycle. After that the capacity drops fairly rapidly; it is essentially zero about the 21st cycle.

We tested the second D cell, and it essentially followed the behavior of the first. At about the 5th cycle it ruptured. Again, we feel that this probably reflects the fact that there was moisture, water in these materials. However, we don't know completely what is the cause of the problem.

We have looked at one of the prismatic cells which are from one of the better batches. The second batch you can see out here. Essentially it starts out at about 3-ampere-hour capacity, rises to about 4 ampere-hours, and stays constant to about the 18th cycle. I don't have the actual data here. Beyond the 18th cycle, one can no longer charge it. There is quite a bit of evidence of shorting occurring in all these materials.

(Figure 2-78)

So, let me summarize the conclusions that we have found in this very limited test. Certainly the cycle life of lithium anode is a very important problem. We need a lot more cycles than this. This is an area where we think we can make some progress. It is an area where JPL will be focusing quite a bit of attention.

The impurity control is critical. That is obvious. Everyone knows that. I think this data may reflect just how it can affect some of the performance of the secondary lithium-type cells. One of the main type of failure mechanisms or failure modes, we believe, that is occurring here is the formation of dendrite breakage and subsequent shorting.

## DISCUSSION

GROSS: EIC has been successful with considerably more cycle life on some cell designs than the one that you tested. Has it not been determined what the differences were?

SOMOANO: I think there were problems with the scaleup, and probably Gerhart may address some of these questions in his talks. They certainly got much more cycle life in laboratory cells than in smaller cells.



## OBJECTIVE

TO DEVELOP IMPROVED AMBIENT TEMPERATURE  
SECONDARY LITHIUM BATTERIES WHICH WILL  
SATISFY NASA'S FUTURE NEEDS FOR ENERGY  
DENSITY, CYCLE-LIFE, AND SAFETY

Figure 2-69



## SCHEMATIC DIAGRAM OF A SECONDARY Li/TiS<sub>2</sub> BATTERY

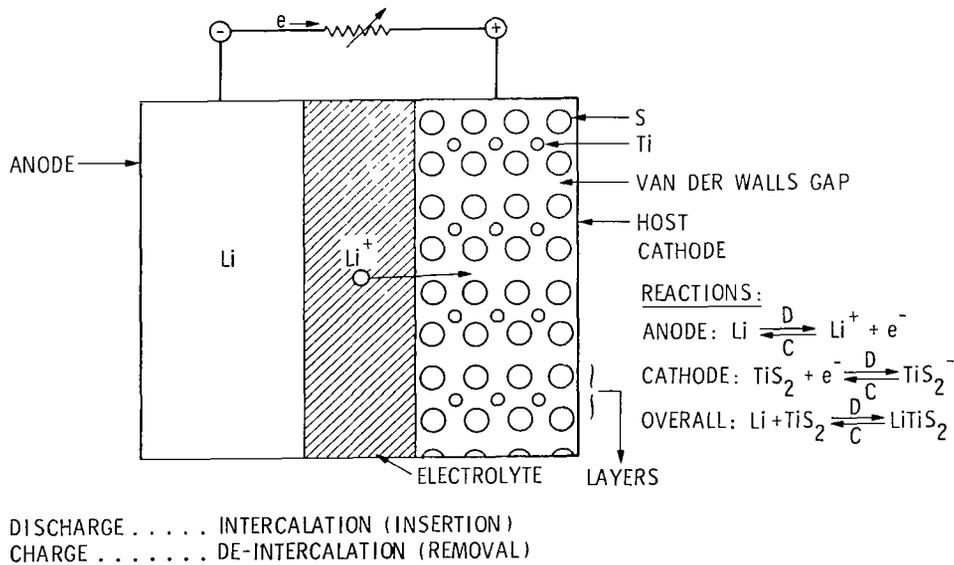
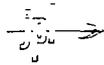


Figure 2-70



## SUBTASKS

- ANODE SUBTASK
- ELECTROLYTE SUBTASK
- CATHODE SUBTASK
- BATTERY TESTING AND EVALUATION SUBTASK

BASIC RESEARCH PROGRAM INVOLVING STUDIES OF FUNDAMENTAL ELECTROCHEMICAL PROCESSES

Figure 2-71



## EVALUATION OF AMBIENT TEMPERATURE SECONDARY LITHIUM PROTOTYPE CELLS

### OBJECTIVE

- TO DETERMINE PERFORMANCE CHARACTERISTICS OF STATE-OF-THE-ART PROTOTYPE CELLS
- TO IDENTIFY PROBLEM AREAS, NEAR-TERM DEVELOPMENT NEEDS, AND AREAS REQUIRING FUTURE BASIC RESEARCH

### APPROACH

- EIC FABRICATED PROTOTYPE CELLS FOR JPL EVALUATION
  - CELLS -  $\text{Li/TiS}_2$  W/ $\text{LiAsF}_6$  AND 2-ME-THF AS ELECTROLYTE (~5A-HR DESIRED CAPACITY)
  - EVALUATION - CONTINUOUS CYCLE TEST W/PERIODIC I-V MEASUREMENTS

Figure 2-72

LITHIUM SECONDARY CELL  
LOAD AFTER FIRST JPL CHG AT 0.3 A  
SERIAL NUMBER 78003. JUNE 30, 1979

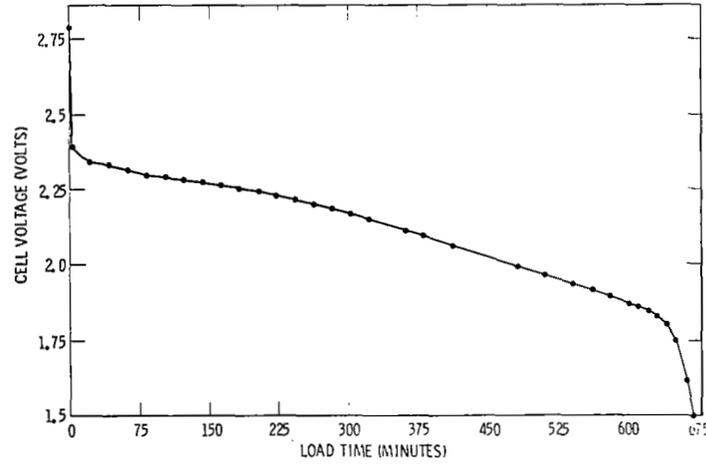


Figure 2-73

LITHIUM SECONDARY CELL, S/N 78003  
FIRST JPL CHARGE AT 0.300 AMPS  
JUNE 29, 1979

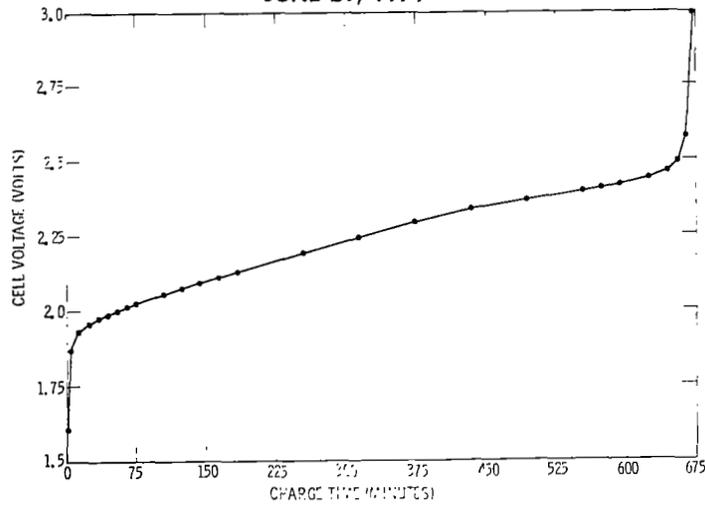


Figure 2-75

SECONDARY LITHIUM CELL 78003  
CELL VOLTAGE VS CHARGE/LOAD CURRENT  
CYCLE ONE, 95% DISCHARGED

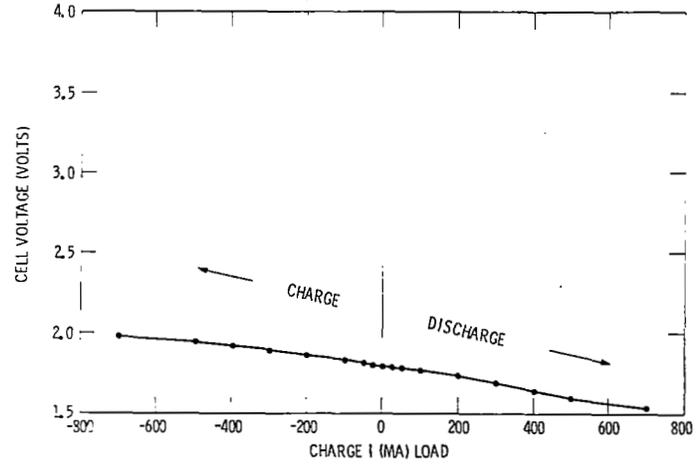


Figure 2-74

SECONDARY LITHIUM CELL 78003  
CELL VOLTAGE VS CHARGE/LOAD CURRENT  
CYCLE ONE, FULL CHARGE

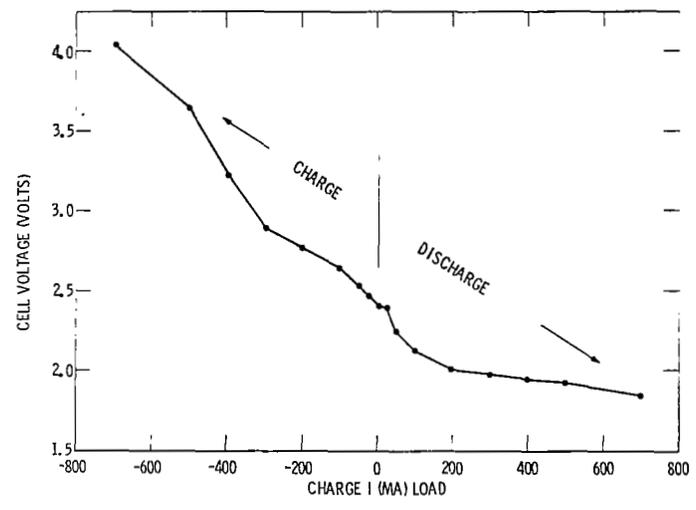


Figure 2-76

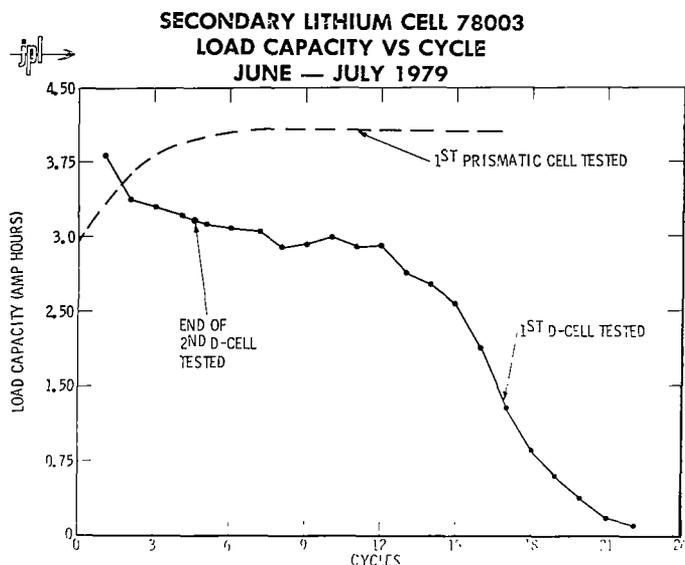


Figure 2-77



### CONCLUSIONS

- CYCLE LIFE OF THE LITHIUM ANODE IS AN IMPORTANT PROBLEM AREA
- IMPURITY CONTROL IS CRITICAL
- FORMATION OF SHORT CIRCUITS UPON CHARGE, DENDRITE BRIDGING, IS AN IMPORTANT FAILURE MODE
- ENERGY DENSITY CAN BE INCREASED BY USING MORE EFFICIENT CATHODE STRUCTURES

Figure 2-78

## RECHARGEABLE AMBIENT TEMPERATURE LITHIUM CELLS

G. Holleck  
EIC

As you have heard today, there are a number of very attractive primary cells already available today. With secondary cells, progress has been somewhat more gradual.

At EIC, we have devoted a considerable effort over the past years in developing ambient temperature lithium cells, in particular, in solving the problem that is common to all secondary lithium cells, which is cycling of the lithium electrode.

Now, the high reactivity of lithium requires very nonreactive solvent. Several solvents appear to be stable if you store lithium in them. This stability is not a thermodynamic stability, but it is a kinetic stability.

You have protective films on the lithium surface which inhibit the reaction. In general, the problem is that you cannot cycle lithium very well in these conditions.

(Figure 2-79)

Let us quickly review what the problems actually are. You can plate lithium quite efficiently out of menthols with 100-percent efficiency. The problems are that the deposit has a bad morphology and comes out dendritization and passivates on stand. Especially on cycling, the efficiency deteriorates rather rapidly.

(Figure 2-80)

In this figure I have indicated a schematic so you can view what happens. But, in plate lithium you plate fresh lithium which covers itself with a protective layer consisting of electrolytes and reaction products with the electrolyte. Some parts might become encapsulated and thus isolated from the substrate.

When you subsequently strip the deposit, part of the lithium will dissolve and part will remain at the electrode. So your stripping efficiencies are less than 100 percent. When you continue the cycle, you accumulate more and more of such isolated material at the surface, and your surface morphology continues to degrade.

This material is predominant with lithium if you analyze it. It is still lithium, but in a form that you cannot get access to by stripping.

(Figure 2-81)

Now, we have approached the system, this problem, in several ways. Let me just point out the two most successful approaches.

We found out that lithium heptofluorarsenate is the best salt precursor that we have found in any electrolyte so far. The reason for this is the reactivity of the salt and the formation of a protective film which has beneficial properties. Most of our experiments have been carried out in THF, which perform better than many other solvents we have looked at.

However, THF heptofluorarsenate solutions are still too reactive for practical secondary batteries. So, the second approach that we took was to modify the ether solvent, in this case, by introducing methyl groups in the alpha position and making it less reactive in this way.

So we relied on a 2-methyl THF: lithium heptofluorarsenate electrolyte as our best present electrolyte for secondary lithium cells; electrolyte preparation, naturally, as a big influence on performance.

(Figure 2-82)

Now, let me quickly show you in the next three figures two items which illustrate the behavior of the lithium electrolytes. These are half-life studies made by Cook in our laboratory.

Here you see, for example, a storage test of lithium and various electrolytes. I would just like to point out that in the type of THF you see a matter of various days depending on preparation methods. In the 2-methyl THF in excess of 10 months of the year, we have not seen any degradation. This is storage. By the way, the temperature is at 71°C.

(Figure 2-83)

This gives you a comparison of cycling efficiency of the lithium electrode as a function of cycle number. In the figure you see typical decay of THF and the much better performance of the 2-methyl THF.

(Figure 2-84)

Another aspect which is important for practical batteries is the reaction of lithium in the electrolyte on open circuit stands. Again, I show you some data comparing THF and 2-methyl THF. After 48 hours, the plated THF has completely reacted or is not accessible by stripping, which does not mean reaction or encapsulation. The 2-methyl THF is still accessible.

There are a few other points that I like to point out. There are areas where we get clearly a larger amount of capacity back than we had before. This is a phenomenon which is very important also for secondary batteries and which we call recontacting. Some of the material that previously had been isolated can be recontacted and can be regained. This is of great practical importance.

(Figure 2-85)

Now, with these data, we were very encouraged to go on and to look at full cells. We built prototype cells with various configurations, button cells, D-size cells, and prismatic cans as you have just heard before with cathodes of the intercalation type, titanium disulfide, chromium vanadium disulfide, and vanadium oxide,  $V_6O_{13}$ .

Common to all of these cathodes is that they intercalate lithium reversibly without decomposition of the host structure.

(Figure 2-86)

This shows you typical cycles for titanium disulfide, lithium titanium disulfide cell. As you can see over the cycles, the general shape, the discharge curve which is characterized by a slightly sloping plateau at a voltage of about 2 volts does not really change much. Actually it decreased somewhat. The curves have not changed.

The upturn at the end, these are cathode limited cells and on charge the increase in voltage. So, you get the voltage increase, and you would get this until some other reaction naturally will take over eventually. But it is fairly distinct.

Let me say one other thing. Most of our long-term testing has been done with titanium disulfide cells, and maybe I should first look at the next two figures.

(Figure 2-87)

This is a typical charge-discharge curve for a lithium vanadium disulfide cell. It is characterized by a similar slightly sloping discharge at about 2.4 volts, higher voltage than the titanium disulfide and similar type of charge.

(Figure 2-88)

This is a discharge charge of a lithium vanadium oxide cell. Here you have actually three plateaus; one less than the one up here, 2.5 volts, and at about 2.2 volts, and on charge followed the same multistep process.

(Figure 2-89)

Now, most of the extensive cycling has been carried out with titanium disulfide cells. The cycle regime that we have used consists of full depth cycles between preset voltages, 1.6 volts on discharge, for example, and 3 volts on charge at about the 6-to 10-hour rate.

This is somewhat different from what you normally do in cycle testing of conventional cadmium cells. They constitute a much more severe cycle regime. I have summarized some cycle results from small cells. These are naturally cathode-limited cells, and you see a slight decrease in capacity with cycle number.

For example, we have reduced the column density by half, and the capacity has come up to the initial value which is a clear indication that the cathode structure is the main determining factor here, not the decomposition of the cathode material. But a change in cathode structure produces this activity.

(Figure 2-90)

Now, having shown that you can cycle such cells, it naturally becomes interesting at what performance you can expect from realistic cell configurations. Using realistic cathode, formulations, and packaging, I have calculated here energy densities for E-size cells, and I have plotted it as a function of the lithium anacode efficient, which was naturally a very important factor for two different cathodes. In the cathodes, naturally the degree of cathode utilization is an important factor in determining your energy density.

You get these type of curves where you see that with a titanium disulfide cell, you can expect somewhere between 80 and 140 watt-hours per kilogram. With a lithium vanadium oxide cell, the range is somewhat larger from about 110, 120 to almost 300 watt-hours per kilogram.

It is interesting to note that a lithium electrode deficiency naturally plays a role in all of these cells, but it comes in much more strongly if you go to a higher energy density cathode. There it makes a large difference on what your electrode performance actually turns out to be.

(Figure 2-91)

This shows the same type of effect on radiometric energy density, and here again you cut off, depending on the lithium electrode efficiency for titanium disulfide to a range of about 180 to almost 400 watt-hours per liter and for the vanadium oxides, 210 to somewhere up here.

(Figure 2-92)

Now, let me summarize the status of the secondary lithium cells.

Two-methyl THF lithium heptafluorarsenate has shown the best cycling performance to date, and it has exhibited excellent behavior on stand.

Laboratory cycling results were verified in complete cells, so we think the feasibility of a lithium titanium disulfide cell, for example, with a cycle life of 100 cycles, have been demonstrated.

Practical cell configurations have attractive energy densities, between 80 and 290 watthours per kilo, and 175 to 800 watthours per liter, depending on the system, specific system.

## DISCUSSION

**BROADHEAD:** How many ampere-hours of lithium did you use in your D cells and your prismatic cells?

**HOLLECK:** Well, we have built a number of cells, and it naturally depends on what cycle life you design the cell for; how much more you put in. In the small cells that I have shown you, the lithium efficiency is in the mid-90 percent. I don't quite remember how much lithium is in the large cells, 10-mil electrodes, and I have to calculate what that comes out to be with the specific capacities.

# WHAT ARE PROBLEMS WITH RECHARGING LITHIUM ELECTRODE?

- PLATING EFFICIENCY  $\sim 100\%$  BUT STRIPPING EFFICIENCY  $< 100\%$ .
- DEPOSIT DENDRITIC.
- DEPOSIT PASSIVATES ON STAND.
- EFFICIENCY OF DISCHARGE DETERIORATES ON EXTENDED CYCLING.

Figure 2-79

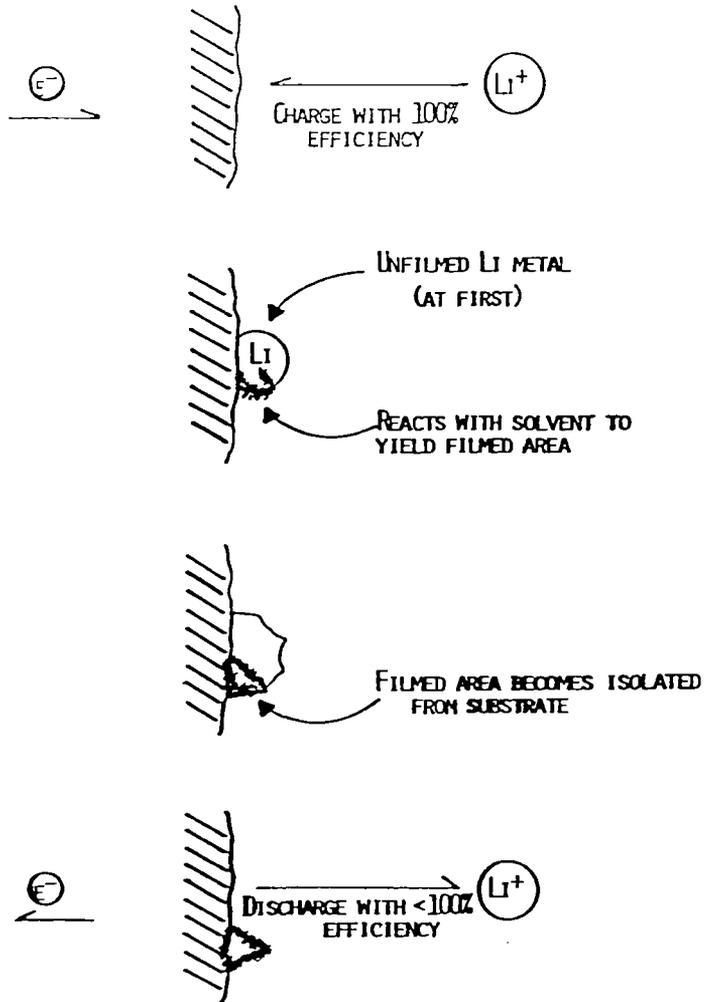


Figure 2-80

## IMPROVED Li CYCLING

- $\text{LiAsF}_6$  BEST PRECURSOR
- MODIFIED ETHER SOLVENT (2ME-THF)
- ELECTROLYTE PREPARATION

Figure 2-81

### THE ONSET OF Li REACTION WITH CYCLIC ETHER BASED ELECTROLYTES AT 71°C

PURIFI- CATION PROCEDURE	1M $\text{LiAsF}_6$ / THF	1M $\text{LiAsF}_6$ / 2-ME-THF	1M $\text{LiC}_2\text{O}_4$ / 2-ME-THF	1M $\text{LiAsF}_6$ / 3-ME-THF	1M $\text{LiAsF}_6$ 2,5-DI-ME-THF
NONE	2(16) <sup>a</sup>	-	-	-	-
A <sup>b</sup>	25(28)	13 Mo	-	-	-
DAPA <sup>c</sup>	4(7)	>10 Mo	6 Mo	10(4)	12 Mo

<sup>a</sup>OBSERVABLE Li CORROSION AFTER 2 DAYS; OBSERVABLE ELECTROLYTE COLORATION AFTER 16 DAYS.

<sup>b</sup>SOLVENT PASSED THROUGH ALUMINA.

<sup>c</sup>SOLVENT DISTILLED; PASSED THROUGH ALUMINA; SALT ADDED IN THE COLD FOLLOWED BY PREELECTROLYSIS; ELECTRODE PASSED THROUGH ALUMINA.

Figure 2-82

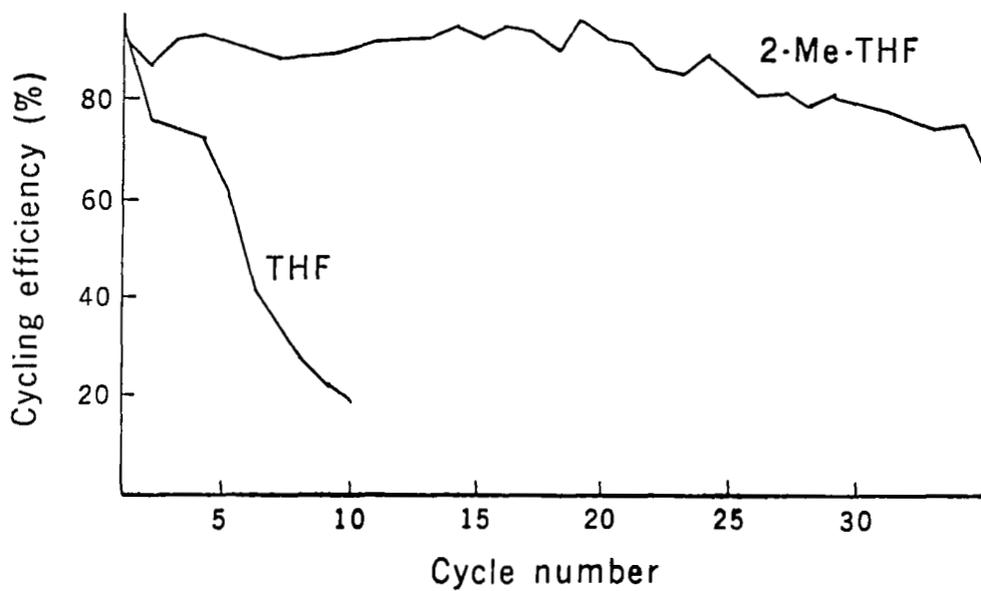


Figure 2-83

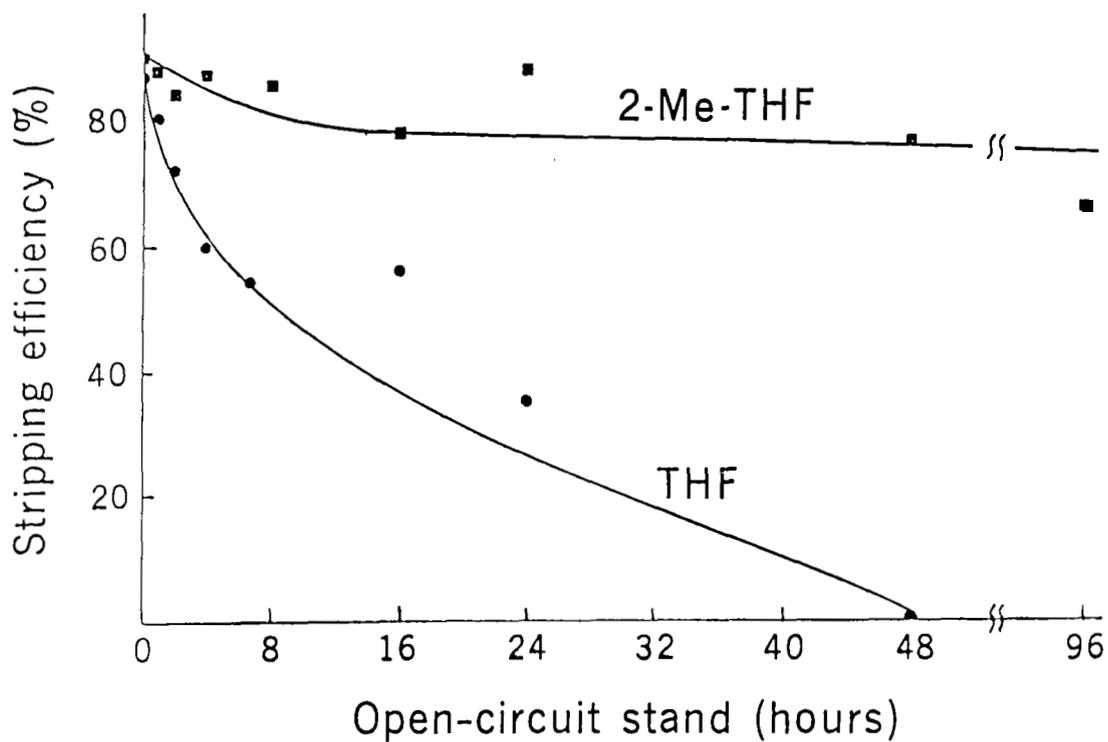


Figure 2-84

## PROTOTYPE CELLS

- CATHODES:  $\text{TiS}_2$   
 $\text{Cr}_x\text{V}_{1-x}\text{S}_2$   
 $\text{V}_6\text{O}_{13}$
- CONFIGURATIONS: BUTTON CELLS  
D-SIZE CANS  
PRISMATIC CANS

Figure 2-85

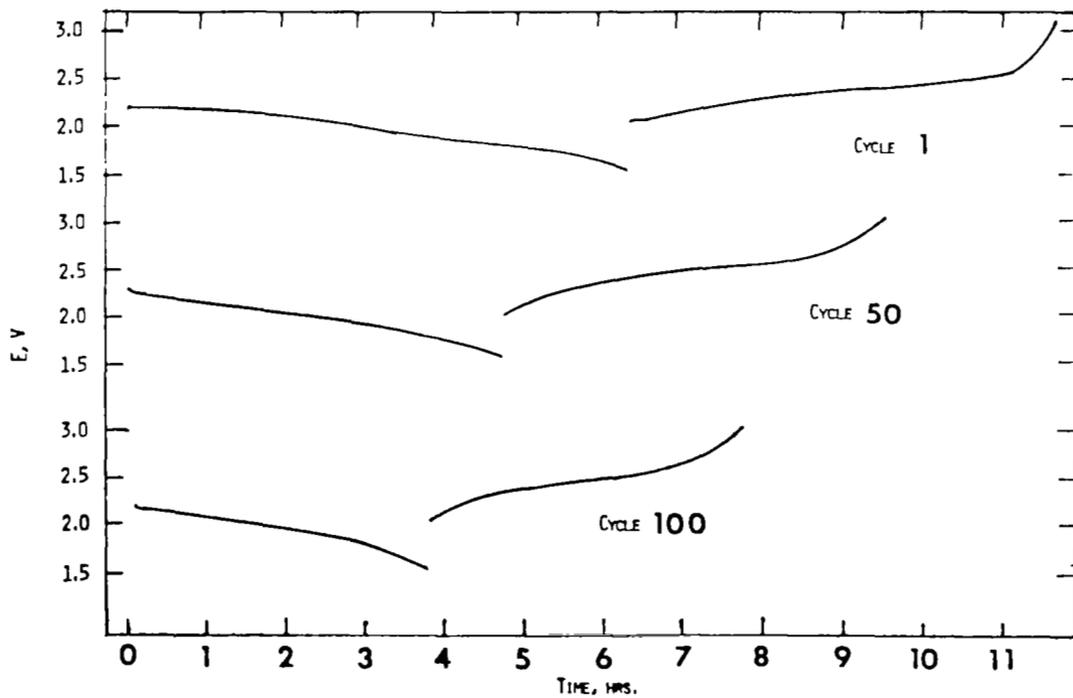


Figure 2-86

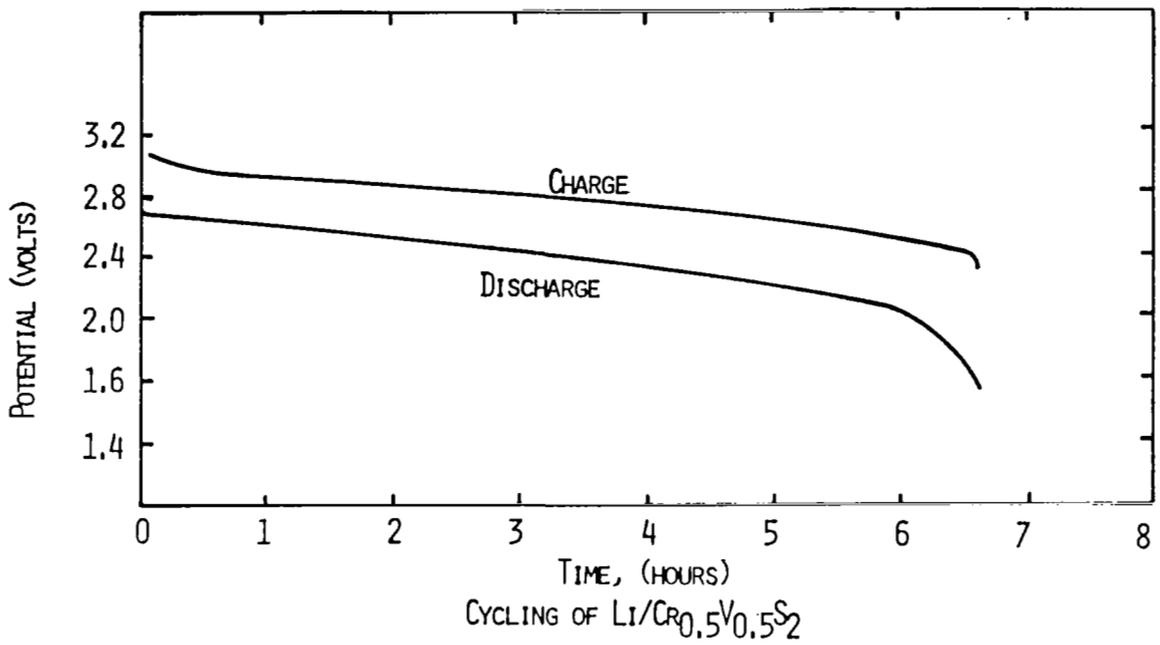


Figure 2-87

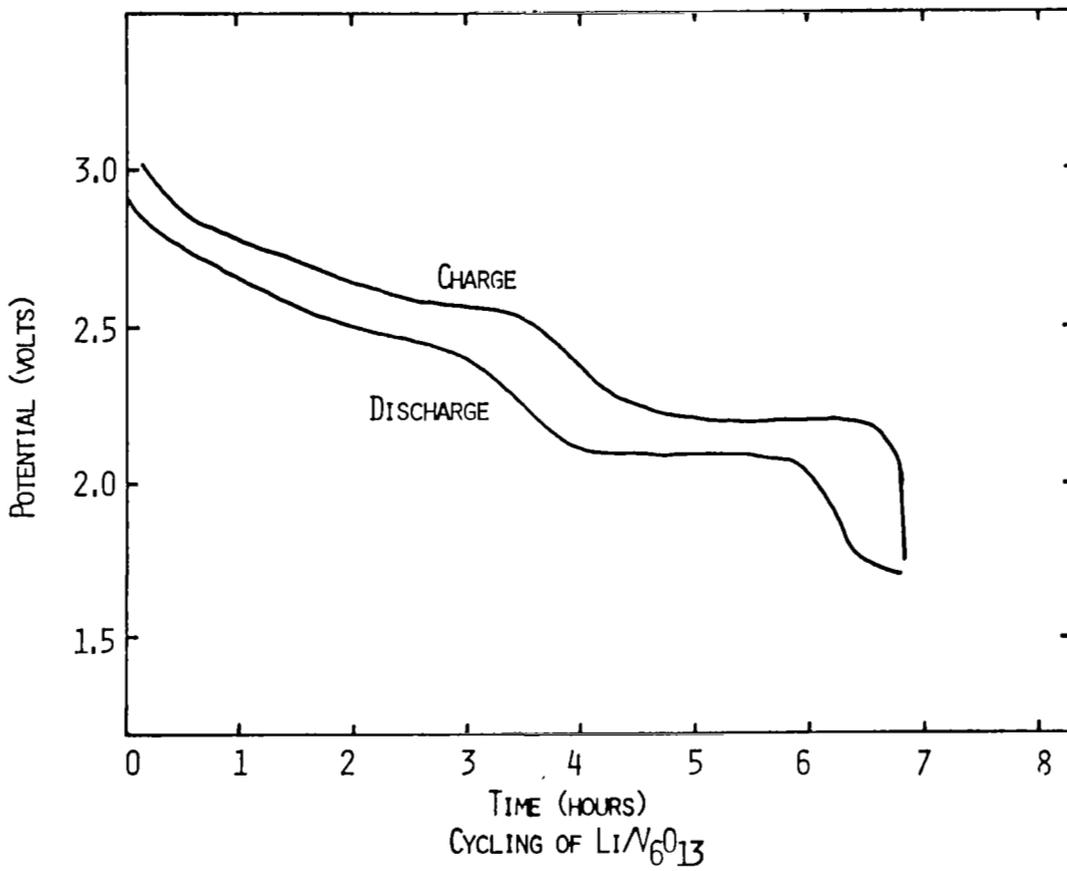


Figure 2-88

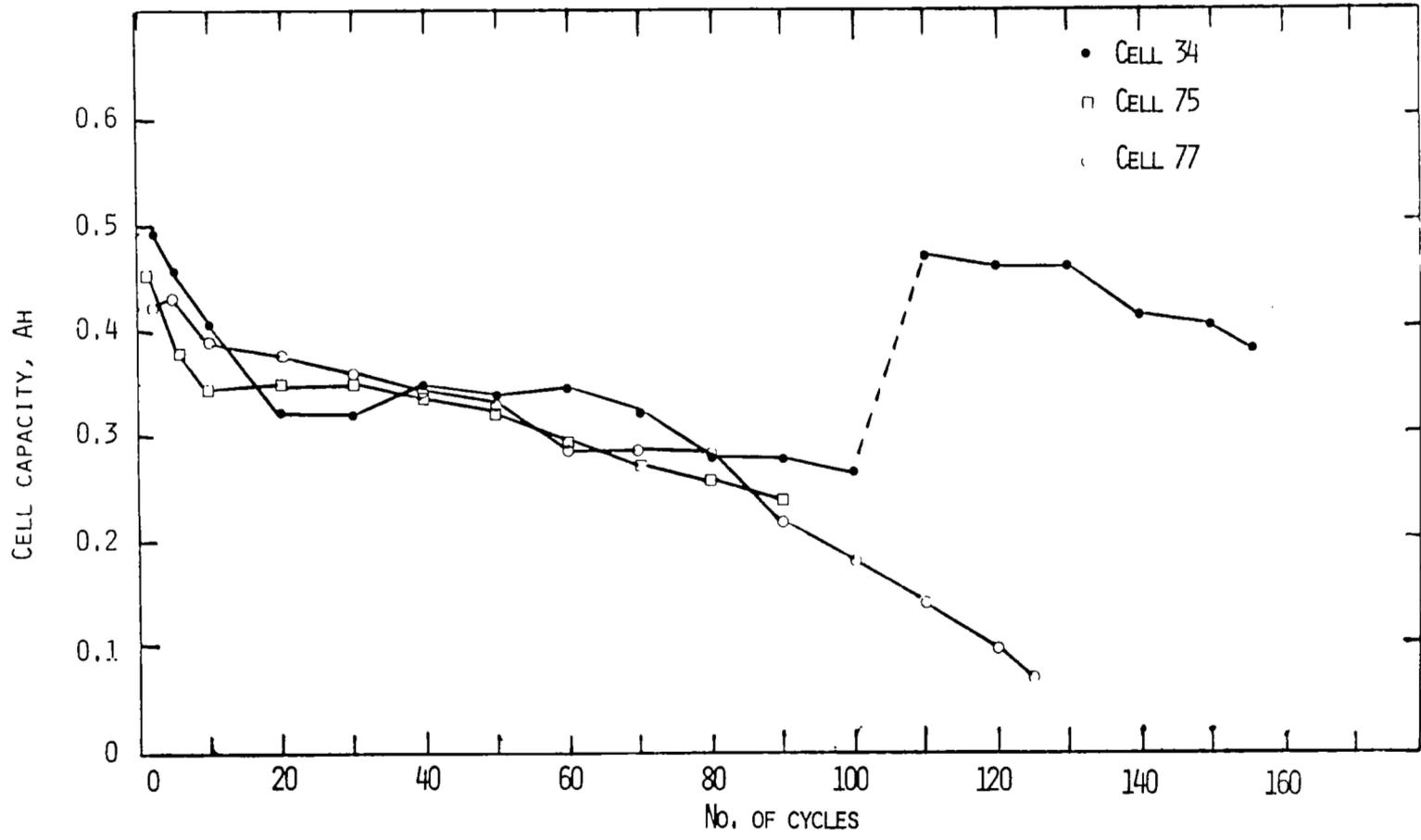


Figure 2-89

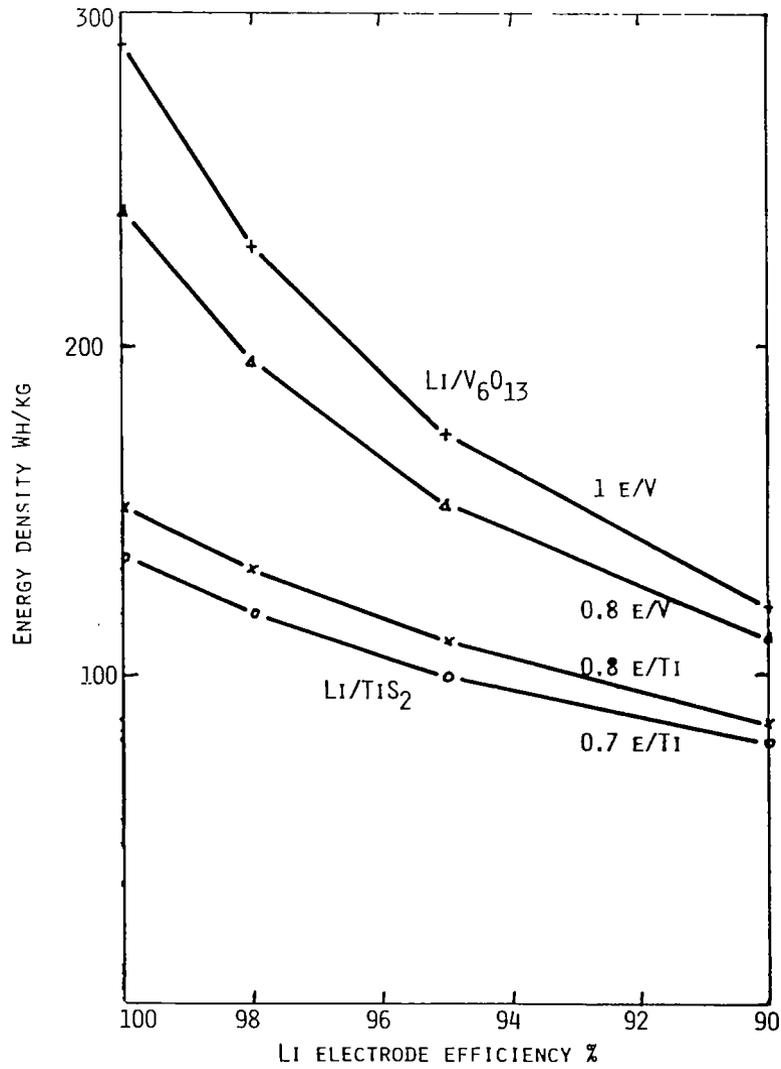


Figure 2-90

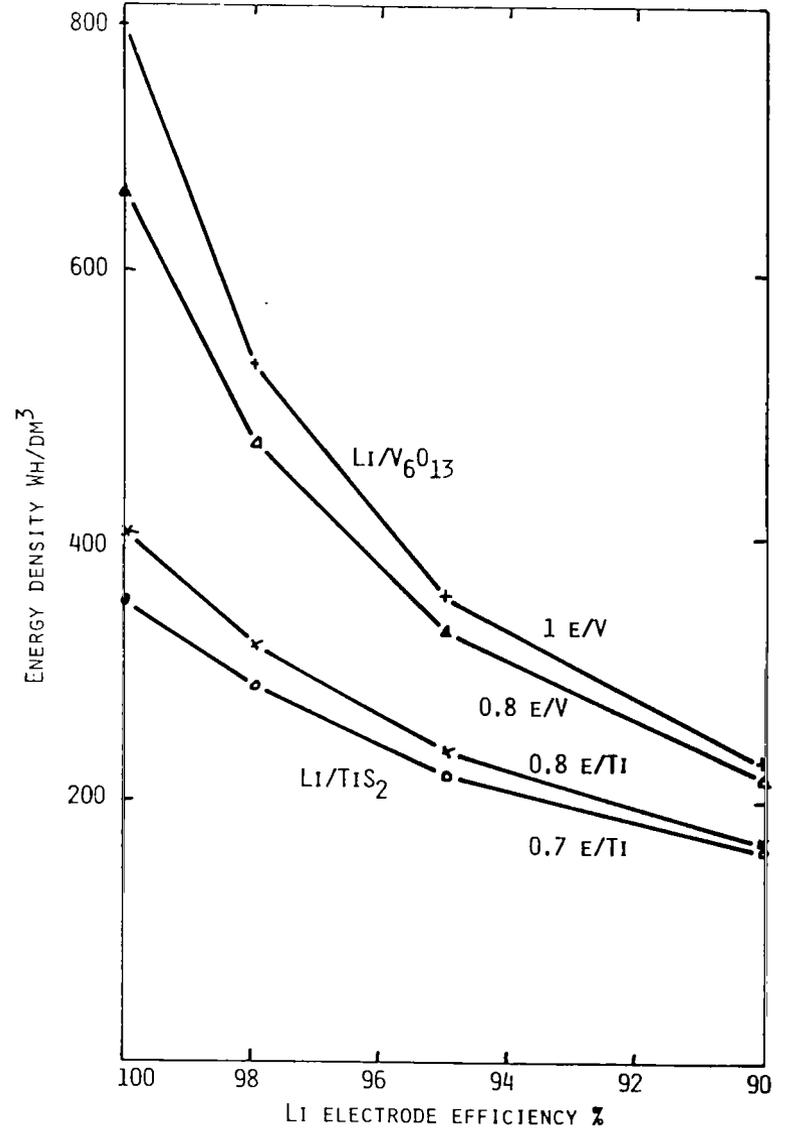


Figure 2-91

## STATUS OF SECONDARY LI CELLS

- 2ME-THF/LI/AsF<sub>6</sub> SHOWS THE BEST CYCLING PERFORMANCE TO DATE. EXCELLENT BEHAVIOR ON STAND.
- LABORATORY CYCLING RESULTS VERIFIED IN COMPLETE CELLS.
- FEASIBILITY OF 100 CYCLE LI/TIS<sub>2</sub> CELL DEMONSTRATED.
- PRACTICAL CELL CONFIGURATION HAVE ATTRACTIVE ENERGY DENSITIES (80 TO 290 WH/KG, 175 TO 800 WH/l)

Figure 2-92



## THE EXXON RECHARGEABLE CELLS

P. Malacheský  
Exxon

The Battery Division of Exxon Enterprises was formed about 2 years ago with the goal of commercializing an ambient temperature look in secondary cell technology based on the titanium disulfide cathode.

What I am going to talk about this afternoon is some of the basic elements of the cell design and discuss some of the performance of the two very limited performance button cell products which have been developed. These limited performance products were developed for micro-electronic applications which require low drain rate and do not require very many deep cycles as typically encountered in solar rechargeable watches and clocks.

(Figure 2-93)

The first vugraph shows the typical requirements for a solar rechargeable watch. Your average discharge rate is on the order of 2 to 3 microamperes. This requires about 20 milliampere-hours per year of watch operation. To maximize the charge acceptance when the solar watch will be in the presence of sunlight, you have to have fairly good charge rate acceptance in the vicinity of 1 to 2 milliamperes.

A very important factor, particularly for analog quartz watches, is that the cell impedance should stay below 100 ohms. Otherwise, the voltage of the watch module will cause the watch to stop operating.

(Figure 2-94)

The next vugraph shows some of the characteristics of the two cell sizes which were developed: the LTS 90 and the LTS 25. The LTS 90 was made to be a technology sampler, although it does have some potential applications in solar rechargeable clocks. The LTS 25 was specifically designed for watch operation. The LTS 25 is essentially a small version of the LTS 90. They both have the same overall cell heights. We have used in these cells a lithium aluminum anode. This was to get around some of the problems that Gerhart has mentioned of the reactivity of lithium with the electrolyte and to try to bring the voltage of the battery as close to 1.5 volts to make the watchmakers happy. So the voltage range of the cells is on discharge between 2 volts and 1.4 volts.

The cell capacity of the LTS 90 is about 90 milliampere-hours, the LTS 25 about 25 milliampere-hours. This calculates to volume densities of about 1.8 hours per cubic inch. The cell impedances are 7 ohms and 25 ohms, roughly proportionate to the area difference. Cell discharge rates which I will talk about later are less than 10 percent per year.

(Figure 2-95)

This vugraph shows the basic button cell assembly. The cells are hermetically sealed, and they have a projection weld with a glass-to-metal seal. The TIS to cathode is just a cold-pressed cathode that runs at about 7 percent porosity. This high-cathode porosity lets the cells be filled rather rapidly so that they can be made in fairly large-volume production.

A two-layer separator system is used with an absorber, a microporous separator, and the anode; the lithium aluminum anode is formed by making a randomate of lithium foil, aluminum foil, and electrolytic action after the cell is closed. The lithium aluminum anode is formed *in situ*.

(Figure 2-96)

The next vugraph shows a typical discharge and charge curve behavior of the LTS 90. You have a typical sloping voltage of a titanium disulfide cell. This has an advantage to some people that can be used as a measurement of the state of charge of the battery.

On charging the cell, however, the cell behaves more like a lithium titanium disulfide cell because at these charge rates you are not letting your lithium equilibrate with the aluminum so that the cell behaves very much like a lithium cell in charge. But, you then have as much of a possibility of dendrite formation because you are using the alloy.

(Figure 2-97)

The next figure shows the deep discharge performance of the watch-size cell. The cells are typically tested in accelerated testing at the C/100 rate on discharge and at the C/50 rate on charge. On these deep type of discharges, you see a fading capacity from initial value of around 23-milliampere values at the accelerated test rate down to maybe around half that rate, the value after seven deep cycles.

The main reason for this degradation in capacity of the cell is that your lithium aluminum alloy anode is mechanically unstable under these deep discharge conditions.

(Figure 2-98)

The next figure shows, however, what happens when you subject these cells to shallow depth discharges rather than deep depth. What we are comparing is the rise in cell impedance as we cycle the cells in terms of dicumulative capacity.

The shallow depth discharge conditions are done under the conditions of 1-milliampere discharge and 1/2 milliampere charge to a capacity of 1 milliampere-hour. You can see there is a big difference in the rate of impedance growth between deep discharge and shallow depth discharge. In terms of the shallow depth this is essentially the number of discharge cycles that the cells have been put through.

(Figure 2-99)

The next vugraph shows some idea of what the cell can do after being subjected to these rather shallow discharge conditions.

This shows some data for the LTS 25. The cell had initial impedance of about 24 ohms. It was given at 25 percent depth of discharge to 6 milliampere-hours. Then, it was put through the shallow cycle at 5-percent depth of discharge for essentially 211 cycles.

During this time the cell impedance rose to about 60 ohms. It was then given three deep discharges. You can see that there is still appreciable capacity now in these cells after these extended shallow cycles, and the cell impedance is still below 300 ohms maximum.

(Figure 2-100)

Turning now to look at the storage capability of these cells, we initially began looking at one month's storage at 65 degrees as simulating 1 year in ambient temperature, relating down to 3 months at 65 degrees.

This shows some storage capability for the LTS 90. This is the 1-inch diameter cell. The initial cell impedances – this is for an average of five cells – is about 5 ohms. After 3 months at 65 degrees, there is a barely detectable rise in the cell impedance.

The first discharge is essentially equal to a fresh cell,  $95 \pm 5$  milliampere-hours. After the first recharge, the cell impedance has gone down from 17 ohms to 9 ohms. There is decrease and increase of impedance between charge and discharge. This is typical of this type of cell because of the volume changes that occur.

(Figure 2-101)

Just to sort of give everybody an idea of what this type of cell can do without the lithium aluminum alloy which severely limits this deep discharge performance, here is some data obtained in the 1-inch diameter cell using the electrolyte that was developed, which was developed at EIC.

We ran this to try to compare with our own in-house developed electrolytes. This is the 1 mil hexofluorarsenate in 2 methyl THF. It is discharging essentially now at the 20-hour rate and is being charged at roughly the 50- or 60-hour rate.

Initial cell capacities are very good. They are about 40- or 50-milliampere-hours higher than the lithium aluminum anode cells, but at about between 20 and 25 cycles you start to see an increase in the cell impedance which is plotted here also from the values down in the 20s to values up in the 40s and 50s. And you see a dropoff in cell capacity.

If you drop the rate back as Gerhart also gave an example, the cell capacity does go back up. This is typical rate fading for a TIS to cathode.

(Figure 2-102)

The next vugraph shows some temperature testing that we have also done with this electrolyte in this cell configuration. We stored the cells for 1 month at 65 degrees. After this time, the cell impedance does go up a little bit. It just about doubles. But, your primary discharge capacity is still there. It is a little bit decreased, but we don't have really a lot of data.

We put the cell through 5 discharge cycles. The capacity dropped down to 74 milliamp-hours. We put the cells back in the oven for another month at 65 degrees. This is a very severe test for a lithium secondary cell for that active lithium which has been plated to let it have a chance to react with the electrolyte. After the second storage period at 65 degrees, we do see some dropoff in cell capacity. After a 10-deep discharge, the capacity is down to around 50 milliamp-hours.

(Figure 2-103)

I would like to summarize where we think this technology is now. These cells are ideally suited for solar rechargeable watch applications. They offer the user a hermetically sealed high-energy density cell that has excellent shallow-depth cycle life as would be encountered in a solar rechargeable watch.

Some of the cell capacity measurements are discharge data that go out to a total milliamp-hour capacities in the vicinity of 250 to 300 milliamp-hours. This is essentially equivalent to more than 10 years of watch operation.

They show the elevated temperature storage capability which is indicative of the basic material compatibility, and this type of cell charging behavior can be readily adapted to photovoltaic cells.

The cell design work was carried out by Chuck Morgan. The titanium disulfide materials, storing and electrified processing, was handled by Robert Francis. Oscar Montefusco and Antonio Romero took care of cell production and animation. Bruce Carstensen and George Galin took care of the cell dilution cycle.

Before I finish, I would just like to tell everyone that this limited cell technology is available for licensing. And anyone interested in it could contact Dr. Robert Hamlin at the Battery Division.

## DISCUSSION

VASANTH: I would like to know whether these cells could be used to promote Diamonds' pattern principle in liquid crystal display watches?

MALACHESKY: The difficulty with using these cells in liquid crystal display watches is that they usually require a backlight which requires current ranges of about 7.5 to 15 milliamperes. These types of pulse requirements severely limit the use of these cells. These cells were made to be used in watches primarily which use the analog quartz mode of operation.

### TYPICAL SOLAR RECHARGEABLE WATCH REQUIREMENTS

AVERAGE DISCHARGE RATE	2-3 $\mu$ A
CHARGE RATE (MAX)	1-2 mA
RANGE OF OPERATION	-10 $^{\circ}$ C/50 $^{\circ}$ C
CELL IMPEDANCE (MAX)	100 OHMS

Figure 2-93

RECHARGEABLE LITHIUM TITANIUM DISULFIDE CELLS

	LTS-90	LTS-25
DIAMETER, IN.	1.05	0.455
HEIGHT, IN.	_____	0.13
VOLTAGE RANGE	_____	2.0-1.4
CELL CAPACITY, mAHS	90	25
W HR/IN <sup>3</sup>	_____	1.8
CELL IMPEDANCE, OHMS	7	25
SELF-DISCHARGE	_____	10%/YR

Figure 2-94

BUTTON CELL ASSEMBLY

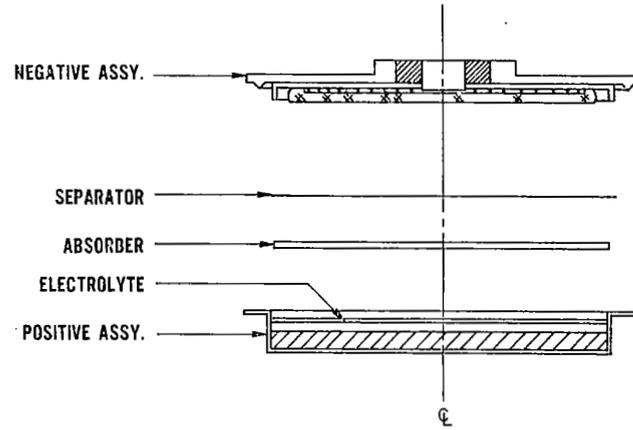


Figure 2-95

174

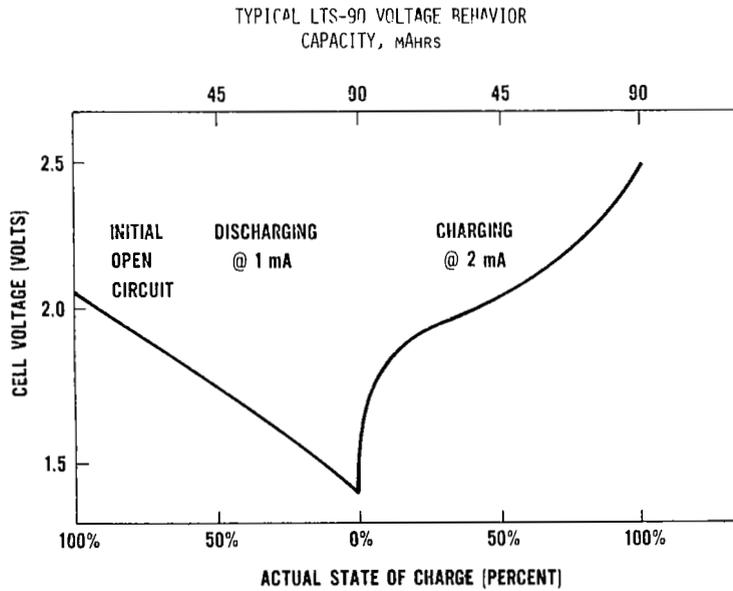


Figure 2-96

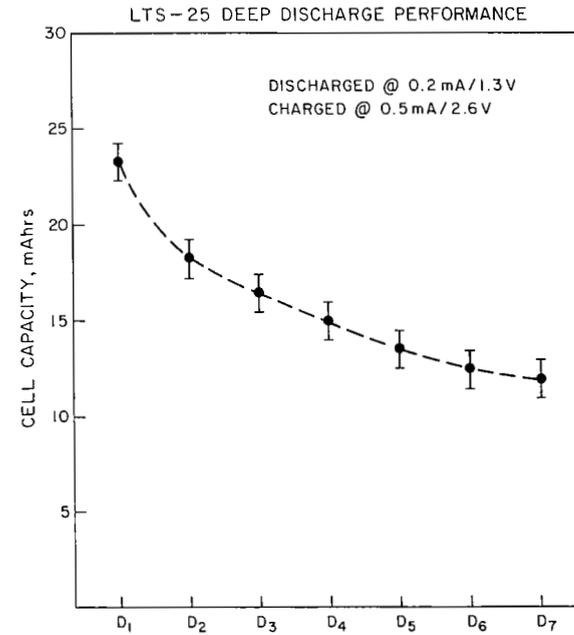


Figure 2-97

# LTS-25 IMPEDANCE GROWTH TURNOVERS OF NOMINAL CAPACITY

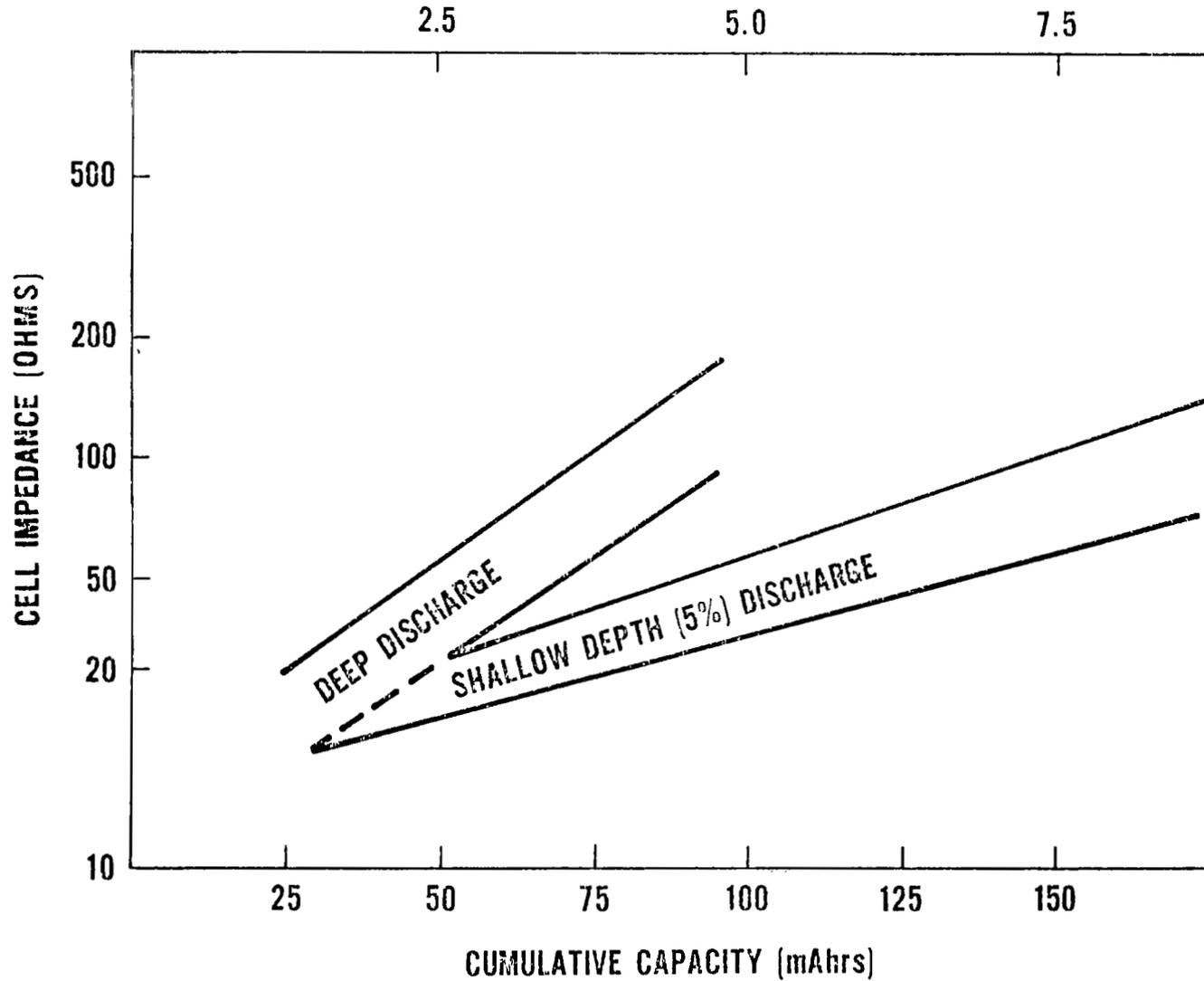


Figure 2-98

LTS-25 ENDURANCE TESTING

<u>CONDITION</u>	<u>CELL CAPACITY, MAHRS</u>	<u>CELL IMPEDANCE, OHMS</u>
INITIAL	-	24
25% DISCHARGED	6	22
SHALLOW CYCLING (5%DOD)	211	60
DEEP DISCHARGE #1	15	34
DEEP DISCHARGE #2	19	63
DEEP DISCHARGE #3	17	68

Figure 2-99

LTS-90 STORAGE CAPABILITY

	<u>IMPEDANCE OHMS</u>	<u>CAPACITY, MAHRS</u>
INITIAL	5	-
1 MONTH @ 65°C	5	-
2 MONTHS @ 65°C	6	-
3 MONTHS @ 65°C	6	-
AFTER FIRST DISCHARGE	17	95 ± 5
AFTER FIRST RECHARGE	9	

Figure 2-100

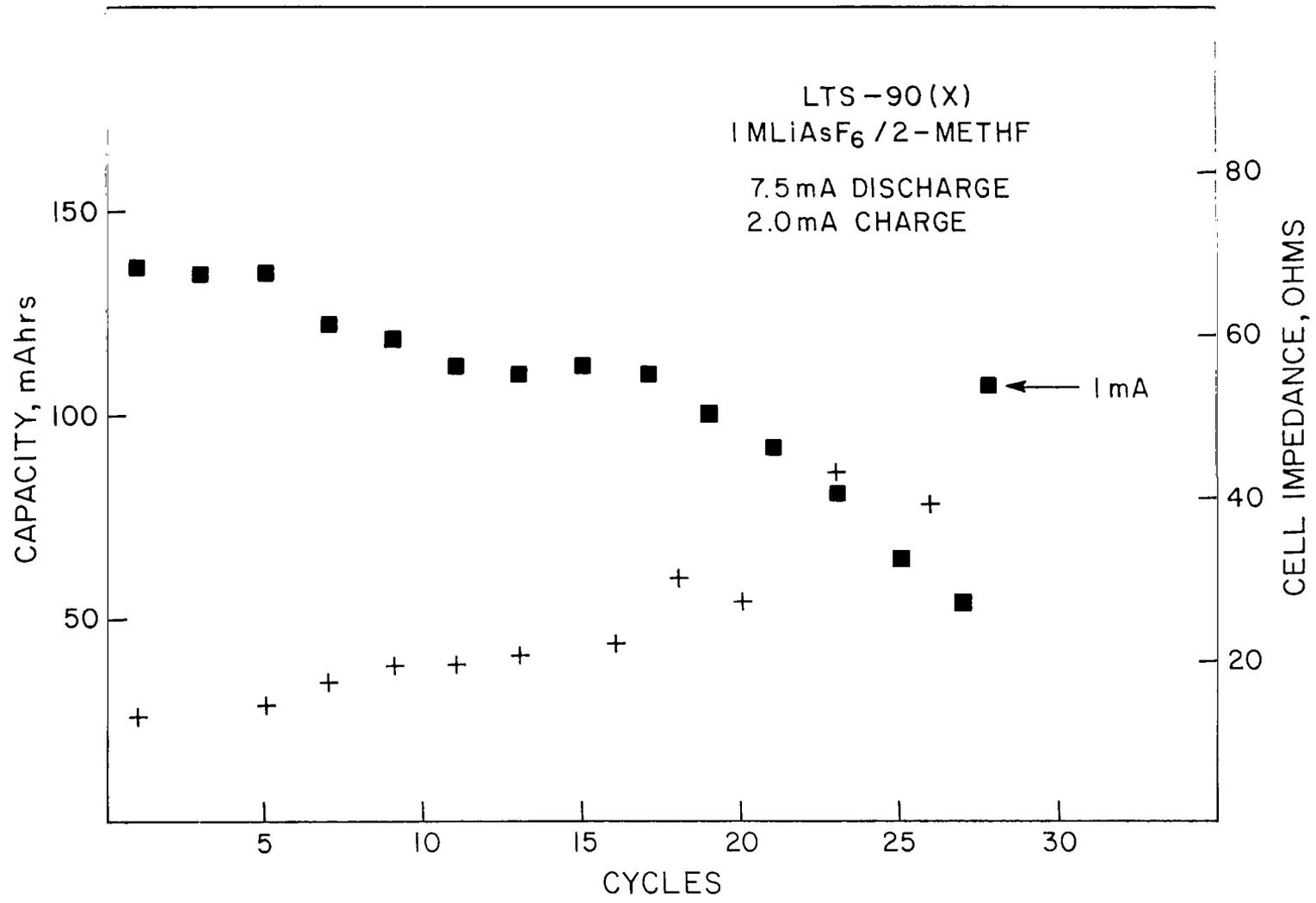


Figure 2-101

## LTS-99(X) ENDURANCE TESTING (LIASF<sub>6</sub>-2METHF)

<u>CONDITION</u>	<u>CELL CAPACITY, MAHRS</u>	<u>CELL IMPEDANCE</u>
INITIAL	-	37
AFTER 1 MO. @ 65 <sup>0</sup> V	114	74
AFTER DEEP DISCHARGE #5	74	43
AFTER 1 MO. @ 65 <sup>0</sup> C	54	64
AFTER DEEP DISCHARGE #10	49	49

Figure 2-102

### SUMMARY

RECHARGEABLE LiAl/TiS<sub>2</sub> BUTTON CELLS ARE IDEALLY SUITED FOR SRW APPLICATIONS SINCE THEY OFFER THE USER:

- A HERMETICALLY SEALED, HIGH ENERGY CELL
- EXCELLENT SHALLOW DEPTH CYCLE LIFE
- ELEVATED TEMPERATURE STORAGE CAPABILITY INDICATIVE OF BASIC MATERIALS COMPATIBILITY
- CELL CHARGING BEHAVIOR READILY AMENABLE TO PHOTOVOLTAIC RECHARGING

Figure 2-103

## HIGH TEMPERATURE STORAGE CHARACTERISTICS OF LITHIUM SULFUR DIOXIDE CELLS

T. Watson  
PCI

My presentation today concerns the high-temperature storage characteristics of lithium sulfur dioxide batteries. This subject was of particular interest at last year's battery workshop, since it was reported at that time that some limitations in shelf-life capability was experienced during prolonged high temperature storage.

Let me start my discussion by introducing basic problems and their historical background.

The lithium sulfur dioxide battery system has attracted considerable interest in recent years due to its wide operational temperature capability, its high energy density characteristics, and its inherent stability and capacity retention during prolonged storage at elevated temperatures.

However, as the applications for lithium SO<sub>2</sub> batteries expand, the performance expectations and shelf-life requirements are often extended by the potential users.

Of particular interest are recent studies directed toward quantitatively determining shelf-life limitations and the associated failure mechanisms. In the course of these studies, it was observed that corrosion of the insulated glass seal within hermetically sealed cells resulted in premature cell failure during prolonged high-temperature storage. A procedure has now been developed which eliminates or significantly retards this corrosive process.

The lithium SO<sub>2</sub> electrochemical system was originally packaged within a nonhermetic enclosure using an elastomeric gasket which was mechanically crimped to form a compressive seal between the cell cover and its casing.

(Figure 2-104)

However, as shown in the first figure this design allowed the gradual diffusion of sulfur dioxide over prolonged storage periods, the rate of which was dependent on cell diameter and storage temperature. For example, the SO<sub>2</sub> diffusion rate of a D cell was observed to be 1.3 milligrams per day at 70°F as compared to 9.6 milligrams per day at 160°F.

The effect of this SO<sub>2</sub> diffusion on cell performance was later verified on nonhermetic D cells stored at 70°F for a period of 6 years as shown in the next figure.

(Figure 2-105)

These results demonstrated a capacity retention of 85.8 percent, which is equivalent to a decay of approximately 2.4 percent per year; a reduction which correlates primarily to the loss of sulfur dioxide.

(Figure 2-106)

The hermetically sealed lithium SO<sub>2</sub> cell as shown in the figure was subsequently developed to eliminate the SO<sub>2</sub> diffusion and to improve overall capacity retention to all temperatures. This design incorporates as a positive terminal, an insulative hermetic glass seal located within the top structure of the cell. The glass seal consists of a central terminal and a steel body which are fused to a glass preform to effect an hermetic compressive seal, the leak rate of which has been measured to less than  $2 \times 10^{-8}$  cc's per second of helium.

Cells of this construction were subsequently stored at 160°F for 1 year, and capacity measured at periodic intervals.

(Figure 2-107)

The results indicated in the figure show an initial capacity loss of approximately 15 percent during the first 2 months, followed by a period of relative stability through the ninth month. However, at the twelve-month interval, the remaining cells were not able to support a resistive load, in this case, 1.9 ohms, and subsequent analysis showed the cells to be in a state of complete discharge.

Upon examination of these discharged cells, it was observed that the glass seals were severely corroded across its insulated surface. Subsequent analysis of this corrosive material showed evidence of lithium deposited within the glass structure, presumably by a replacement mechanism with metallic fillers present within the glass structure. Such corrosion apparently resulted in the formation of a conductive path across the insulative glass causing parasitic self-discharge of the cell.

An extensive program was subsequently conducted to characterize this specific failure mechanism and to institute appropriate corrective action. Alternative glass formulations and selected glass barrier coating materials were evaluated within cells stored for prolonged durations at 185°F, an increased temperature level that was selected to accelerate the corrosive reaction.

Candidate materials were analyzed alongside control samples for comparative study. Acceptance criteria for an effective barrier material included the following:

First of all, stability within the electrolyte; second, surface adhesion over a broad temperature range; third, a suitable viscosity for application of the coating; and finally, satisfactory dielectric properties.

While some glass formulations appear to perform better than others, all eventually showed evidence of corrosive degradation after 12 weeks storage at 185°F.

Successful results, however, were achieved using a two-part barrier coating material, which was applied to the internal surface of the glass seal and was cured under a predetermined thermal profile. The results obtained on cells utilizing coated seals versus uncoated control samples are illustrated in the next group of figures.

(Figure 2-108)

Before I comment on these photographs, let me just make a few general observations. First of all, the corrosion process on uncoated samples appears to be electrochemical in that it propagates radially from the seal body toward the central positive terminal as a function of storage time.

The coated seals, however, remained intact throughout the test period and exhibited no evidence of embrittlement or degradation. Subsequent removal of the barrier coating showed the glass surface completely intact and free of corrosion.

Now, this figure shows two groups of cells: one with an uncoated glass-to-metal seal that is shown on the left side, and those cells with a coated seal as shown on the right. As you can see, at week number 4 at 185°F, the corrosive reaction is well underway. And as you can see in the left photograph, it is emanating from the body of the glass-to-metal seal toward the central terminal.

As you can see in the right-hand photograph, the coated seal is free of any embrittlement or cracking. The adhesive bond is in excellent condition. When the coating is physically removed, the glass appears to be in its original state.

(Figure 2-109)

Here we are at week number 8. As you can see, the corrosive material has almost completely covered the insulated glass surface on the two left photographs. But, as you can see on the right, the coated seal remains intact, and physical removal of the coating shows the glass to be again in its original condition.

(Figure 2-110)

This is week number 10. At this time, the uncoated seals are completely covered with the corrosive material, and a conductive path has now formed from the body of the eyelet to the central terminal. This is the point of time in which I describe the resulting parasitic self-discharge phenomenon. Within a fairly short period of time, the cell has completely discharged once the seal is in this corrosive state.

Again, on the right-hand view, we see that the coated seal again appears to be completely intact and free of any corrosive material. Upon removal of this coating, the glass seal is again free of any evidence of corrosion.

(Figure 2-111)

This was the final week of the study. This was 12 weeks at 185°F. By this time, the corrosion has not only covered the insulative surface, but has even started to migrate up the central terminal of the glass-to-metal seal. This sometimes results in open circuit of the cell if the discharge has not been completed by this point in time.

The coated samples again showed no evidence of corrosive attack, even after 12 weeks at 185°F. Again, removal of the coating at this point in time shows the seal to be in its original condition without any evidence of cracking or deterioration.

Capacity retention data for these test cells are shown in the next figure.

(Figure 2-112)

Control samples with uncoated seals showed a slight loss in cell capacity after 2 weeks storage at 185°F, followed by a pronounced loss after 4 and 6 weeks, and were unable to support a resistive load after eight weeks.

Examination of these cells indicated that self-discharge of the cell had occurred. Cells containing coating seals, however, were extremely stable by comparison and delivered approximately 85 percent of initial capacity after 12 weeks' storage at 185°F.

This data clearly demonstrates the effectiveness of the barrier coating in preventing glass-seal corrosion with the resulting improvement of shelf-life characteristics and overall capacity retention at elevated temperatures.

In conclusion, it can be seen that the development of hermetically sealed lithium SO<sub>2</sub> cell eliminated the problem of SO<sub>2</sub> diffusion and its adverse effects on shelf life. However, successful use of this hermetic design requires that the problem of glass-seal corrosion be addressed, specifically the resulting parasitic cell self-discharge phenomenon.

An effective solution to this problem has been developed, which will significantly enhance the overall reliability, shelf life and capacity retention characteristics over a wide temperature spectrum. This new development will now permit successful implementation of the lithium SO<sub>2</sub> system in many new and more demanding applications and environments.

## DISCUSSION

BENNETT: I want to thank you for doing this study as a result of some of the questions I raised last year. But, were these done in the invert, or were these upright?

WATSON: We conducted some tests in various orientations, both with the central terminal up-down, as well as horizontal. We found that the worst-case condition occurred with the terminal in the down position, although in all cases the corrosive reaction occurred. In some cases it would take 8 weeks; in some cases 10 weeks. But it was just a matter of time before the corrosion resulted, regardless of the orientation of the cell.

BENNETT: I was rather curious about the fact that you said in every case the corrosive product was conductive. As I mentioned last year, I had some cells that were on at 140°F for 3 1/2 years. In no cases was the corrosive product conductive, even though 60 percent of the glass seal was gone after that period of time.

Do you have any comments on that?

WATSON: The results of the testing that we have conducted showed, in all cases in the cells that we tested, partial discharge of the cell had occurred. In some cases it was not complete discharge. The resistive path in some cases is quite high, and the length of time for the cell to be completely discharged, especially a large-size cell with a lot of capacity, might take longer than the test period which you ran.

Most of the cells we ran our tests on were primarily 1-ampere per hour and 8-ampere per hour cells. And the phenomenon seemed to show itself up fairly quickly.

VASANTH: My first question is, which method was used in order to detect the corrosion; chemical, visual, or microscope?

WATSON: We initially used a visual examination to determine that it was electrochemical. I don't know how all the photographs appeared from where you sat. But it does clearly show, if you look at them closely, that the corrosive material does migrate radially from the sealed body towards the central terminal.

Now, if this were a chemical versus electrochemical type of phenomenon, I would expect to see the corrosive material occur in random positions along the glass surface. But in all cases it became radial from the outside in.

VASANTH: Did you also measure the rate of corrosion by weight loss method?

WATSON: No. The rate of corrosion was done by a visual observation: by disassembling and examining the cells and observing and photographing the condition of the glass-to-metal seal at various intervals throughout the test.

VASANTH: In other words, it was only qualitative?

WATSON: Qualitative. But we also ran capacity tests, as I showed in the previous figure which showed that the capacity retention was significantly affected as the storage life progressed.

VASANTH: My last question is, have you tried some methods that would suppress the corrosive reaction?

WATSON: I am sorry, would you repeat that?

VASANTH: Corrosive reactions can be suppressed by adding some compounds that would inhibit the reaction. Have you tried some of those?

WATSON: No, we haven't tried any inhibiting materials to add to the electrolyte because we are not quite sure what the mechanism is that is causing this to occur.

We have experimented, and some of the manufacturers of the glass-to-metal seal have experimented with various glass formations. But, to date, they have not been too successful. As I mentioned, some are somewhat better than others, but in all cases, after 12 weeks the corrosion had occurred.

HESS: Can you comment on the recent lithium battery failure that occurred in Bermuda?

WATSON: Yes. I can give you some information on that. As you are probably aware, a complete investigation of that incident is presently being conducted, and I wouldn't want to speculate on the specific causes nor the corrective action that might result from that investigation. But I can give you some limited information based on a preliminary study which I believe has just recently been completed.

That particular incident you referred to was an explosion which occurred or violent event which occurred on a lithium battery incorporating seventy-two 30-ampere hour cells. These were packaged in a series parallel relation with protective fuses and diodes. These cells were hermetically sealed both with a venting mechanism. In fact, in this particular case it was a dual vent to provide a backup safety vent mechanism.

Some of the findings that were determined, at least to date, showed the following:

First of all, the packaging of the battery was done by the user. The user did not follow the specific instructions as recommended by the manufacturer.

There were no provisions for venting any overpressurized electrolyte or gases that might result due to a cell or group of cells venting.

Second of all, the construction of the battery pack itself was a very strong reinforced cylindrical type of container which was not designed to withstand some of the shock and vibration that this battery was subjected to during its use in storage.

Thirdly, and I think most important, is that the user did not follow the recommended guidelines for discharge of the battery. Specifically, the battery was discharged well below the recommended capacity and voltage limitations that were set up by the manufacturer.

JOHNSON: You said that most of your tests were conducted at elevated temperatures. Did you also run control specimens at a low temperature, at room temperature? And if so, could you make a comment as to the rate of corrosion at the higher temperature versus the room temperature?

WATSON: That's a good question. We have done tests both at room temperature and elevated temperatures. Obviously, we have done the elevated temperatures or have concentrated on these primarily because of the time function.

We do have some correlation between 185°F storage versus 160°F storage, again based on visual observations of the glass seal. As you saw from some of my data, 8 weeks or 10 weeks at

185°F is roughly equivalent to approximately 9 months at 160°F. Again this is based on what we observed.

We have not had this glass seal coating for that long a period of time that we could really determine whether it is benefiting us at room temperature. To date, the longest hermetically sealed cells that have been stored are roughly on the order of 3 to 4 years. And in no cases have I observed any significant evidence of corrosion.

So right now I don't have a correlation between what happens at room temperature versus what happens at elevated temperature. But it may be that further studies along about 7 years at room temperature may show up this relationship.

BENNETT: I would like to answer that question somewhat, if I may. Last year we tore apart hermetically sealed lithium sulfur dioxide cells that had been on storage for 3 1/2 years at 140°F, 70°F, and 0°F. We evaluated the quality of the glass seal and the amount of the corrosion product by immersing it in water and collecting the amount of hydrogen gas that was involved. So we had a fairly accurate comparison between them.

The ones that were at 140°F for 3 1/2 years had about 60 percent of the glass, shall we say, dissolve. The ones at 70°F had less than 1 percent. And the ones that were at 0°F were in new condition. That might give you some idea as to what the comparison is between temperatures.

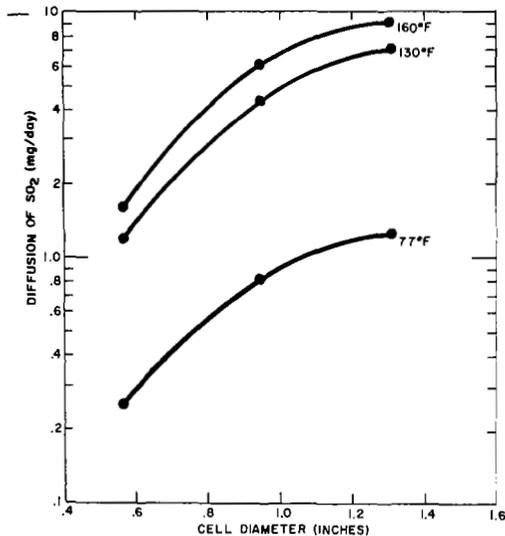


Fig. 1 Diffusion rate through elastomeric seal

Figure 2-104

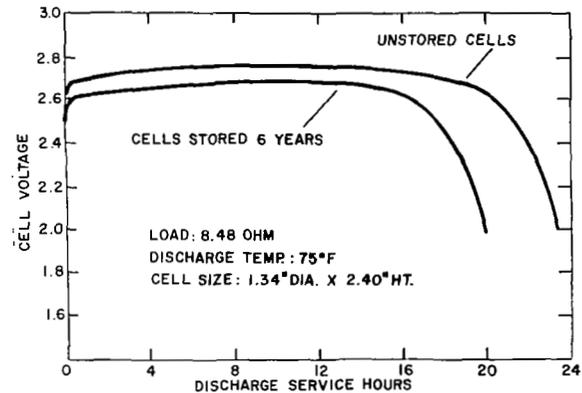


Fig. 2 Shelf life of non-hermetic cells (elastomeric crimp seal)

Figure 2-105

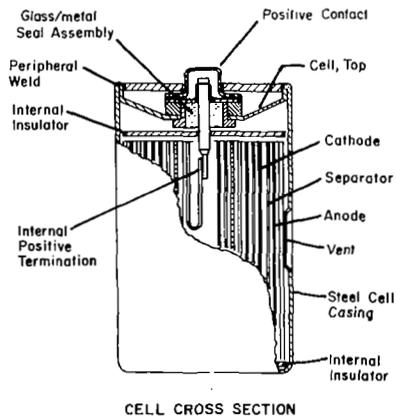


Fig. 3 Hermetically sealed Li/SO<sub>2</sub> cell

Figure 2-106

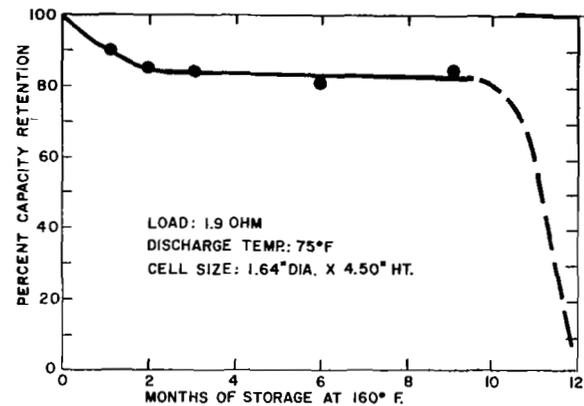


Fig. 4 Shelf life of hermetic cells (without high temperature seal)

Figure 2-107

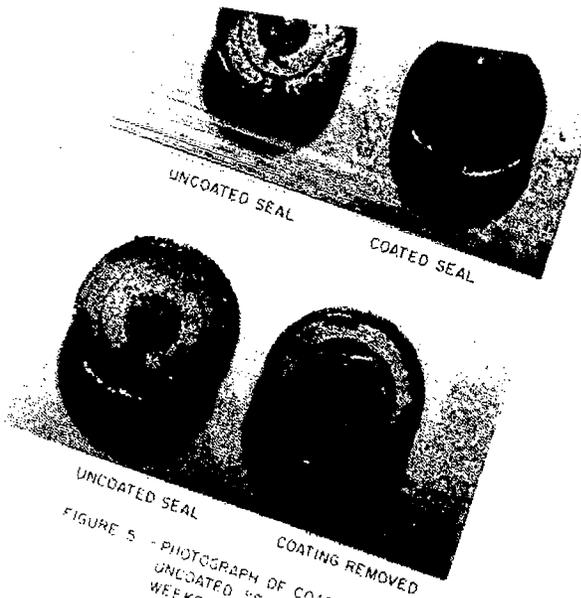


FIGURE 5 - PHOTOGRAPH OF COATED AND UNCOATED SEALS AFTER 4 WEEKS AT 185°F

Figure 2-108

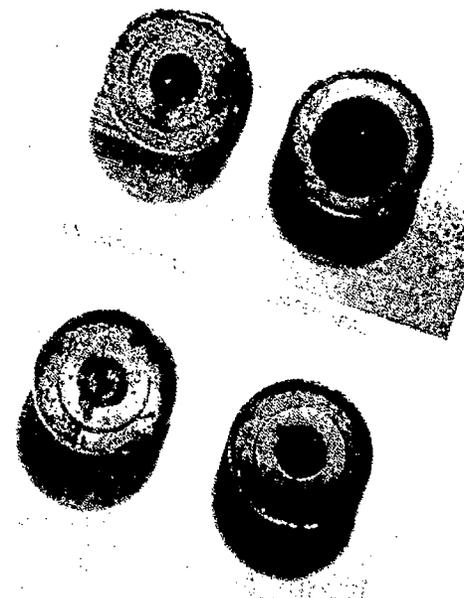


Figure 2-109

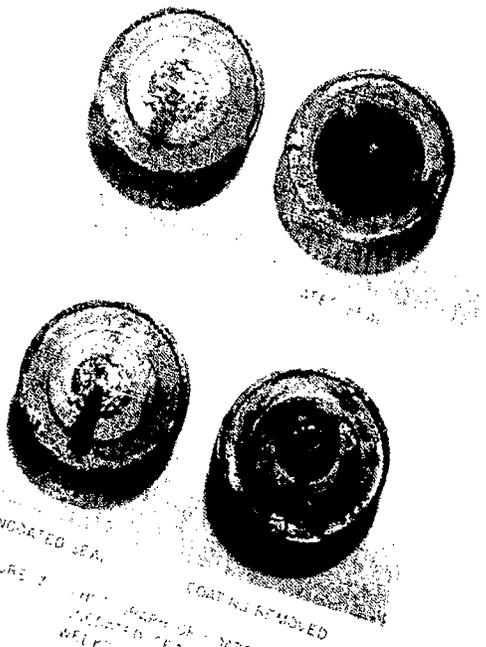


FIGURE 7 - PHOTOGRAPH OF COATED AND UNCOATED SEALS AFTER 12 WEEKS AT 185°F

Figure 2-110

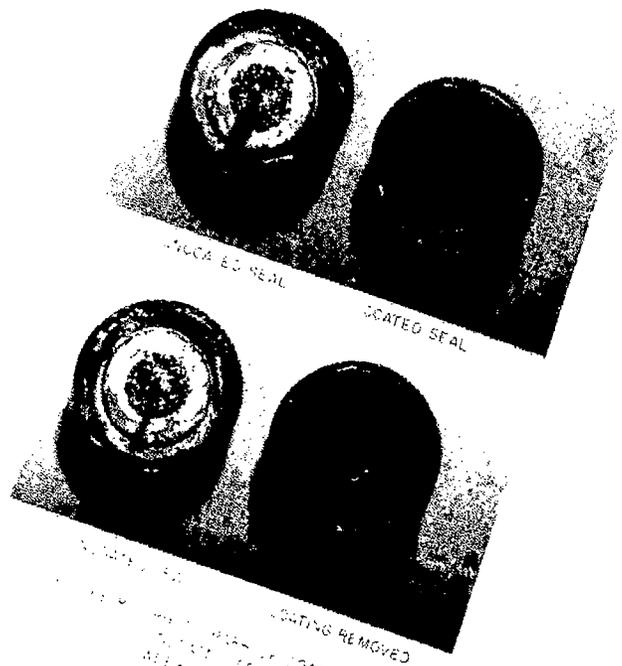


FIGURE 8 - PHOTOGRAPH OF COATED AND UNCOATED SEALS AFTER 12 WEEKS AT 185°F

Figure 2-111

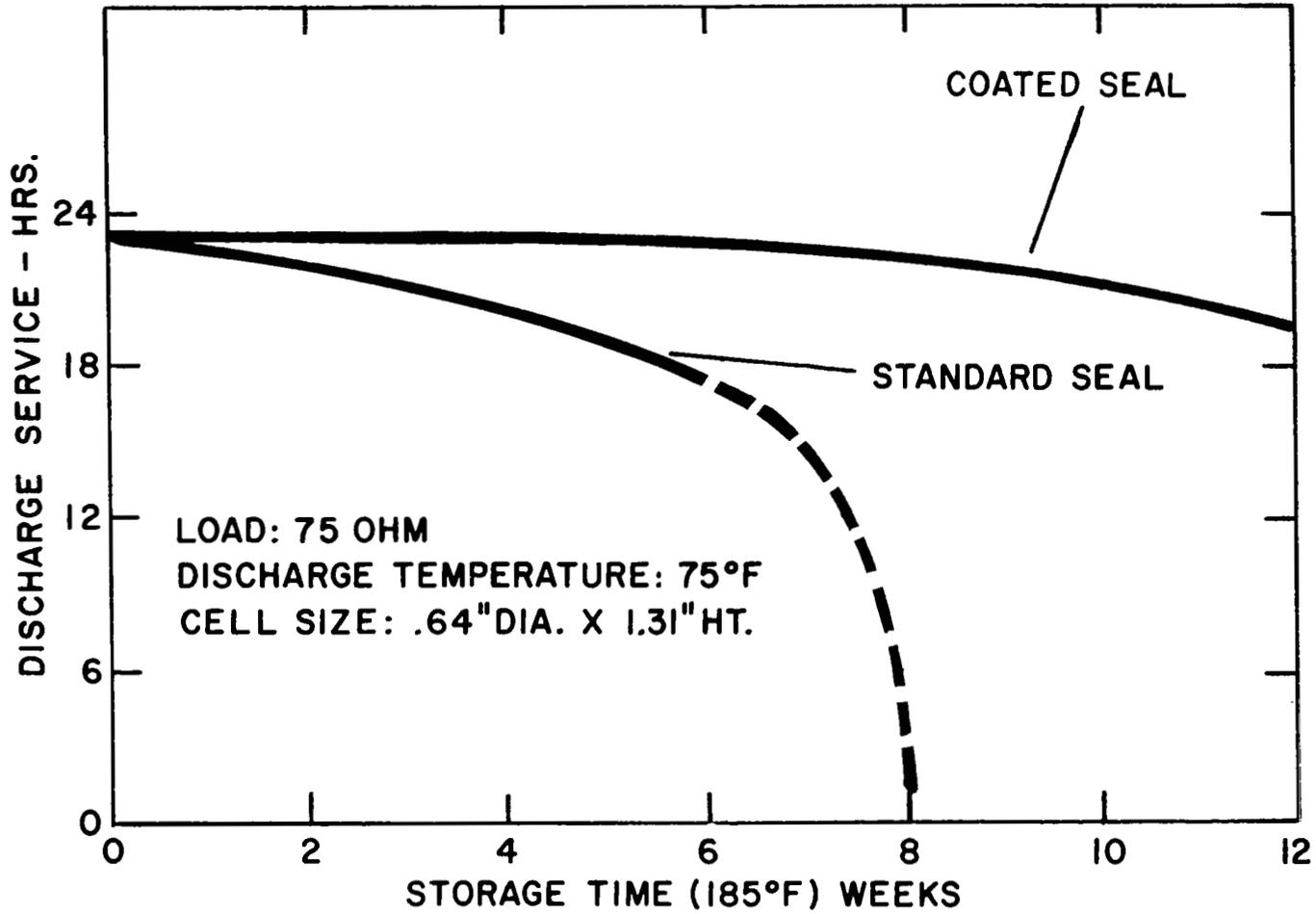


Fig. 9 Comparison of storage (with & without coating)

SESSION III

FLIGHT EXPERIENCE AND BATTERY DESIGN

D. Baer, Chairman  
Goddard Space Flight Center



## NATO – IN-ORBIT EXPERIENCE

J. Capulli  
USAF

My presentation is on the NATO III satellite battery, on the experience we have had. Primarily I will concentrate on NATO III-A and NATO III-B.

The NATO III satellite system is the latest in a series of NATO communication satellites contracted to Ford Aerospace Communications Corporation.

Before I go on, I have two coauthors; that is, John Armantrout of Ford and Wayne Stafford of Aerospace Corporation.

These satellites were contracted to Ford Aerospace. They are managed by the Space and Missile organization. The cells were subcontracted to Eagle Picher, and the battery was fabricated and put together by Ford.

NATO III-A was launched in April 1976; III-B in January 1977; and III-C in November 1978. The satellites are in synchronous orbits and experience two 45-day eclipse seasons per year with the longest eclipse being 72 minutes.

(Figure 3-1)

Briefly, I will go over the electrical power subsystem. They are spinning satellites, and we have about 533 watts at the beginning of life on our solar reactor. We have three 20-ampere hour NiCad batteries with an orbital life of 7 years. This battery weighs approximately 26 pounds.

We have a power-control unit that regulates the batteries. In sunlight we are regulated by partial shunt regulator, and we use a booster.

(Figure 3-2)

Our charge or discharge characteristics are such that we have a ½-ampere and 1-ampere array. When in a full charge mode, we go 1½ amperes. We charge for 5 minutes on battery 1. We put on open circuit for 10 minutes and go to the next two batteries. We are tri-sequenced.

When we are on full charge, we put both arrays in series. Trickle charge is approximately C/4 with a full charge array of about C/13.

That is incorrect where it says both arrays are in parallel. As I said before, we try to sequence the batteries and have had a lot of success handling batteries in that mode.

Next, I will talk about the cell and assembly. Our NATO III battery is a basic type design, lightweight with two end plates and two through-bolts. We have a thermal control on each group of four cells.

(Figure 3-3)

This gives you basically the characteristics. In orbit load is approximately 4 amperes and voltage limit of 30.8 volts. We cut back our charge. There is a little bit more description at the bottom on the type of materials we used on the battery pack.

If we hit a temperature of 85 degrees, we will limit back to trickle charge. We have a heater that is actuated at 40 degrees.

(Figure 3-4)

As far as our reconditioning design philosophy is concerned, we have a 16-ohm resistor which turns out to be reconditioned discharge current of approximately 1.6 amperes. We undervoltage whenever a group of five cells hits 5 plus 1/4 volt.

(Figure 3-5)

To give you a brief understanding of the kind of testing we put the batteries through, at the vendor we have starved and flooded electrode capacity tests. The flooded is when we fill electrode with electrolyte; the starved is as designed.

Factory testing at Ford, at the cell level, we have 20 burn-in cycles and capacity tests at 40, 60, and 70. We have very stringent requirements at the vendors and at the factory. As far as the battery level is concerned, we have vibration and thermal vacuum testing and a capacity test at 40, 60, and 70. And we have several tests at 40, 60, and 70. Those are the basic temperatures that we test at.

(Figure 3-6)

Now, what I am going to try to do is take you through NATO III-A, NATO III-B, and the engineering model or life test battery to give you an idea. You can look at some of these results that we have at the vendor. Keep those in mind whenever we look at the orbital experience that we buy. I guess the key would be a precharge and the negative deposited ratio.

NATO III-As is a bit greater than NATO III-Bs, which is an engineering model. The pickup is the loading. The amount of the electrolyte is listed on the far right.

(Figure 3-7)

We had some slight differences between NATO III-A and NATO III-B, despite handling almost exactly the same with identical thermal environment. We try and figure out why there is

a difference in performance. As you have seen, the NATO III-A batteries tended to have a little bit better factory testing and vendor results than those of NATO III-B. However, NATO III-B has performed better in space.

This indicates our reconditioning. Our capacity cycle is on the far right. On the left side I put 3-hour, 60-degree capacity tests that we had at the battery level.

It will somewhat indicate to you, as we were cycling the batteries, we don't really tend to get a trend at the beginning of life. However, as we go on in life, we tend to get a trend. You can see that the III-A results are slightly less than those of III-B.

I did put capacity for the entire system and not for each individual battery. So you might justify that by three.

(Figure 3-8)

This shows you each individual season that we have had in the battery and end of discharge voltage characteristics for each season, all the way through the season.

The first season is September 1976. Ignore the asterisk at the top. It is not applicable to life of the season. We didn't recondition after the first season. When we went to the second season, which was March 1977, we had a slight decrease in end of discharge voltages. I have that percentage here for you. It turned out to be about a 0.5 percent drop in the discharge voltage without reconditioning.

Then, we went to our third season and we did reconditioning. We lost 2 percent from the first one on the first and the second season. When we reconditioned, we gained back 1.3 percent of that end of discharge voltage. As we continued to see the results that we got in orbit, we were able to predict pretty much where we would be from year to year, in that we seemed to lose from one season to the next without reconditioning, approximately 0.6 percent and we gained back approximately 0.4 percent at the end-of-discharge voltage through reconditioning. Then we went on to our fourth season, and again we did not recondition. Our philosophy is to recondition every other season, which would put us in August just prior to the fall equinox. As you see, we dropped again. I believe we dropped here a little over 2 percent. We then reconditioned again for our fifth season.

Here comes the thing that makes it not apples and apples. As you get toward the end, what happened is that we lost one-half of our load that is a traveling-wave tube amplifier, and we lost that on September 17.

Up to the point halfway through the season, as you see, it really doesn't correlate after that. We went from approximately a 24-percent DOD for a maximum eclipse to what would be about a 16-percent DOD. But we did on that regain 0.4 volt.

(Figure 3-9)

Basically, this slide gives you the same information, except on NATO III-B. If you remember the type of results we got at the vendor and in the factory, it doesn't quite correlate as well as we would expect.

Here's our first season. No reconditioning.

We go to our second season, September 1977, with no reconditioning, and basically, the same discharge voltage characteristics.

Again, we went to the third season. We decided not to recondition for the third season. The third season was the same, and we never lost more than 0.8 percent from season to season without reconditioning for the first three seasons.

We decided to start reconditioning in the fourth season. We regained a little bit, but not much. We regained approximately 0.4 percent. So we are extremely happy with NATO III-B's performance on orbit, but we cannot really explain why it is that much better than that of NATO III-A.

(Figure 3-10)

This will give you an idea on pretty much what the individual discharge voltage curve was for each maximum eclipse. This is our first season maximum eclipse, approximately 70 minutes in October 1976.

This is again without reconditioning. Of course, we lost percentage.

With the third season we did recondition. You can see the shape of the curve flatten out a bit and raised up higher by a few tenths of a volt.

For our fourth season, again we did reconditioning at this point, and we got that dropped down to just a little bit above 23 volts.

Then we did reconditioning again for the September 28 season. We saw it jump up approximately 1 volt. So that reconditioning seemed to help us more as we got further down in the life on NATO III-A.

(Figure 3-11)

Basically, this gives the same information on NATO III-B. You will get an idea on how close these curves are and how we have been able to get pretty close repetitive characteristics on NATO III-B's discharge voltage.

This is our first season.

We go to our second season without reconditioning. Again, we didn't recondition for our first three seasons.

You can see that the first three seasons are almost identical. We have to rather ignore the end because all the equivalents we got were exactly the same as far as length, a few minutes off as far as the discharge curve. It was pretty much the same. We didn't really need to recondition, so we didn't.

Then, we reconditioned for the fourth season, and it gained us just a little bit, not too much.

(Figure 3-12)

We had Ford do a life test for us in which one-half of the battery was reconditioned approximately every other season. The other half of the battery was not reconditioned. This half was the unreconditioned-half of the battery. It did support high loads for 7 years, accelerated life test. However, the accelerated life test was almost down to a few tenths of a volt, approximately what we have seen in one of them. So it has been very well represented.

The other half of the battery was reconditioned. The circles denote where we reconditioned. We reconditioned every other season as we do in space.

Then, as you can see, we plotted the NATO III-A characteristics against the life test.

You see, we weren't quite as good on the reconditioned half as we had expected. As I said, after this one season, NATO III-A will operate at the maximum 16-percent depth of discharge.

(Figure 3-13)

Basically, the same information on NATO III-B. This is the same life test battery, our engineer-model batteries.

Again, we reconditioned halves; this is the reconditioned-half of the battery.

Then, our results are better than the life tests. So, when we looked at all the data, it was hard for us to understand why III-B was that much better than III-A.

The last point on NATO III-B shows about 25.44 volts end-of-discharge volts. That is because we are now in orbital storage on both NATO III-B and NATO III-C. That is with a zero-degree Sun and the wind blows, which puts us about 8-percent DOD on batteries at maximum eclipse, and we will keep it that way until NATO needs to use one of the satellites off III-A.

## DISCUSSION

GASTON: What is the minimum/maximum average temperature?

CAPULLI: During our winter solstice, we experienced very high temperatures and had to manage our batteries, both on NATO III-A and III-B. Those temperatures rose to between 70 and 80°F.

With charge management we cut back the charge, and we got that temperature to go down to the high 60s. That is in the winter solstice.

In summer solstice we are right around 40 degrees during both eclipse seasons—the eclipse seasons closest to the winter solstice. In other words, the tail end of the fall equinox and the beginning of the spring equinox we tend to see temperatures in the high 60s, between 60 and 70. However, whenever we are in the summer solstice, getting toward summer solstice, our equinox seasons, we tend to see temperatures between 40 and 50 degrees.

STOCKEL: Was this a constant current discharge?

CAPULLI: Yes. All three batteries are tied directly to the bus, which is one of the reasons I had only one voltage curve for all three batteries, because all three batteries have identically the same voltages as the discharges.

STOCKEL: I noticed on your accelerated test data, you only had it out to 7 years?

CAPULLI: Yes

STOCKEL: Would you say after 7 years you are getting marginal?

CAPULLI: Maybe I can get one of my coauthors to help me answer that one.

ARMANTROUT: We were beginning to see that at the end of 7 years, it was beginning to tail off on the data you saw up there. However, we believed that it was going to perhaps last for another 2 years if we had kept going, to the end of voltage, that is.

Now, if our end of voltage had been a little lower, these cells had a particularly low voltage plateau. But I believe they would have stabilized in another 2 years at probably about 115 or something like that. We experienced that on our other tests on SMS, about 115 was the number.

DeBAYLO: Can you describe your mechanism for reconditioning? Do you have a fixed resistor that you can put across all battery housings?

CAPULLI: Yes. We can put one battery across a 16-ohm resistor and discharge a battery across there to what turned out to be about 20 to 21 volts. We terminated at that point and recharged to approximately a 1.5- to 2.0-return. We did one battery and then did the next and the next.

DeBAYLO: Essentially to 1 volt per cell?

CAPULLI: Right. However, our undervoltage, as I stated, takes a group of five cells. When that group of five cells—that's five plus a quarter volt—any group of five cells automatically cuts off our reconditioning discharge.

FORD: In your life test cells, were they from NATO III-B or NATO III-A lot? Or was it a different lot?

CAPULLI: Our first lot was lot one.

FORD: Did it really show data on three lots of cells?

CAPULLI: Yes, it did.

GROSS: Could you repeat the DOD that you had in orbit?

CAPULLI: When we started, we were experiencing 24-percent DOD. When we lost three, we went to 16 percent, and orbital storages on III-B and III-C were operating at approximately 8-percent DOD.

GROSS: Do you have information on the current sharing between the three batteries in flight?

CAPULLI: I have that, but not with me. I know each battery has been about 4 amperes, with battery two on NATO III-A and NATO III-B appearing to take a little bit more of the load. Maybe about 4.0 to about 4.4 amperes on that battery with the lowest supporting about 3.8 amperes.

So that is about 0.6 ampere from time to time. Most of the time we were a little bit closer than that.

LACKNER: How many cells did you have in each group? 24?

CAPULLI: 20 cells per battery.

LACKNER: You got down to 23 volts?

CAPULLI: Yes, we got down to about 23 volts on NATO III-A only. We didn't get down that low on NATO III-B. As a matter of fact, I don't think we got below 24 volts on NATO III-B.

LACKNER: You were talking about something like 1.15 volts in the longest eclipse?

CAPULLI: Something like that.

# ELECTRICAL POWER SUBSYSTEM

- SOLAR ARRAY PANEL (upper and lower right circular cylinder)
  - 85 in. DIAMETER BY 88.7 in. HEIGHT
  - 21,256 SILICON SOLAR CELLS
  - PROVIDES 533 W BEGINNING OF LIFE, 421 W END OF LIFE EQUINOX
- THREE 20 amp-hr NICKEL-CADMIUM BATTERIES
  - EACH BATTERY CONSISTS OF 20 CELLS IN SERIES
  - EACH BATTERY WEIGHS 26 lb
  - BATTERIES PROVIDE 304 W IN PARALLEL DISCHARGE FOR 1.2 hr
  - CELL BASED ON EXISTING SMS DESIGN
  - ORBITAL LIFE: 7 yr
- POWER CONTROL UNIT
  - PROVIDES MAIN BUS VOLTAGE REGULATION (29.6 to 28.4 V)
  - PROVIDES THE ELECTRICAL INTERFACE BETWEEN SOLAR ARRAYS, THE BATTERIES, AND THE SPACECRAFT ELECTRICAL LOAD
  - CONTROLS BATTERY CHARGE, DISCHARGE AND RECONDITIONING

Figure 3-1

## CHARGE/DISCHARGE CHARACTERISTIC

### DEDICATED CHARGE ARRAY

- 0.5A ARRAY
- 1.0A ARRAY
- ARRAYS IN SERIES WITH MAIN BUS
- 0.5A TRICKLE CHARGE (C/40)
- 1.5A FULL CHARGE (C/13) BOTH ARRAYS IN PARALLEL

### TRI-SEQUENCE

- 2 REDUNDANT CHARGE SEQUENCERS
- 5 MIN ON CHARGE
- 10 MIN OPEN CIRCUIT

Figure 3-2

### BATTERY ASSEMBLY CHARACTERISTICS

CONFIGURATION	20 SERIES CONNECTED NICKEL CADMIUM CELLS
LOAD	5 TO 7.5 AMPS
DURATION	1.2 HRS MAX (ECLIPSE)
LIFE	7 YR ON ORBIT ( 600 CYCLES)
CHARGE CURRENT	1.24 TO 1.48 AMP (HIGH) 0.35 TO 0.44 AMP (LOW)
CHARGE DUTY CYCLE	1/3 (1/2 OR CONTINUOUS BY COMMAND)
TEMPERATURE	40F TO 70F (85F RESET TO LOW CHARGE) (40F MIN BY ACTIVE HEATER CONTROL)
VOLTAGE LIMITS	30.8 VOLTS MAX/5 VOLTS PER FOUR CELLS (CONTROLLED BY PCU)
WEIGHT	27.03 LB MAX (EP) 30.4 LB MAX (GE)
MATERIALS	TITANIUM SUPPORT RIBS AND END PLATES (HM21A,T8) ALUMINUM THROUGH AND THROUGH BOLTS (2024,T4)

Figure 3-3

### NATO III RECONDITIONING DESIGN

- 16 OHM RESISTOR
- C/12 DISCHARGE RATE
- UNDERVOLTAGE
- ● GROUP OF 5 CELLS REACHES 5.00 + .25V

Figure 3-4

# NATO III Battery Testing

## VENDOR TESTING

- STARVED AND FLOODED ELECTRODE CAPACITY TESTS
- CAPACITY TEST (30°, 40°, 70°, 80°F)

## FACTORY TESTING

- CELL LEVEL
  - 20 BURN-IN CYCLES
  - CAPACITY TESTS (40, 60, 70°F)
- BATTERY LEVEL
  - VIBRATION AND THERMAL VACUUM TESTING
  - CAPACITY TESTS (40, 60, 70°F)

Figure 3-5

## Battery Cell Electrode Characteristics

	PRE CHARGE (AH)	FLOODED ECT (AH)			PICKUP (g/dm <sup>2</sup> )		POROSITY (%)		KOH (g)
		POS	NEG	RATIO	POS	NEG	POS	NEG	
NATO IIIA	3.6	23.0	33.6	1.45	13.34	15.79	84.6	83.7	74
NATO IIIB	3.2	24.4	31.1	1.27	13.25	15.70	85.3	85.0	77
E.M.	5.8	23.0	43.3	1.88	13.52	15.42	83.3	83.3	74

Figure 3-6

### Capacity Measurements

FROM CELL ACTIVATION

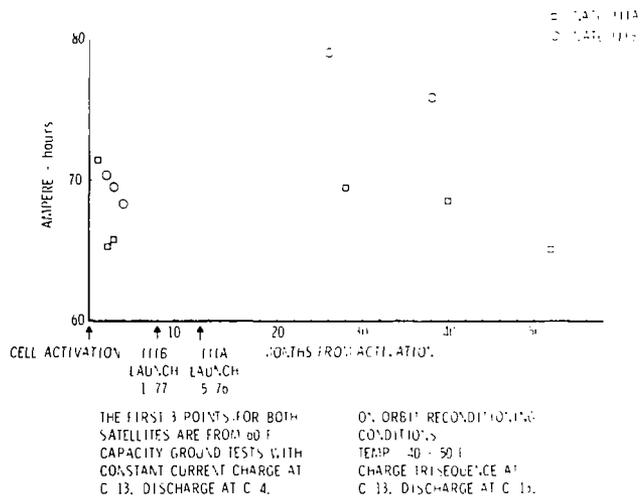


Figure 3-7

### NATO IIIB Comparison of First 4 Seasons Battery Eclipse Voltages (End of discharge)

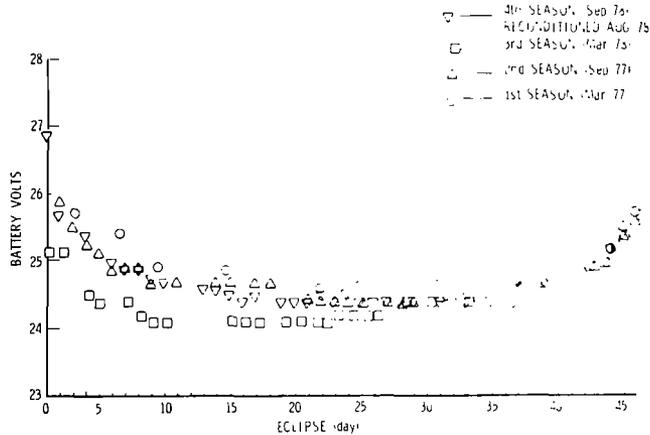


Figure 3-9

### NATO IIIA Comparison of First 5 Seasons Battery Eclipse Voltages (End of discharge)

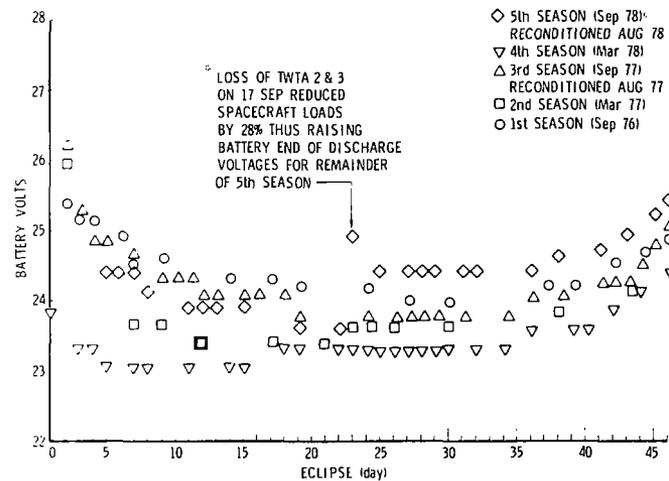


Figure 3-8

### NATO IIIA Max Eclipse Battery Parameters

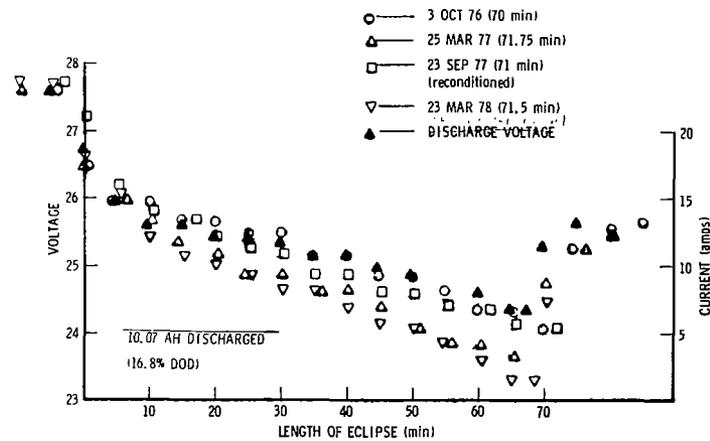


Figure 3-10

# Comparison of NATO IIIB Max Eclipse Battery Parameters - Voltage for First 4 Seasons

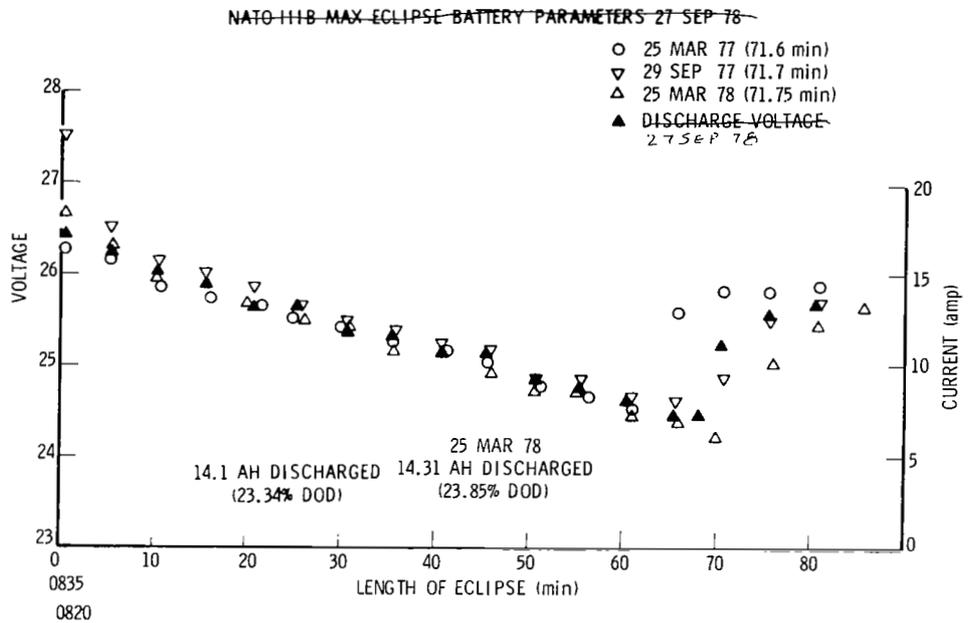


Figure 3-11

# NATO IIIA End of Discharge Voltages

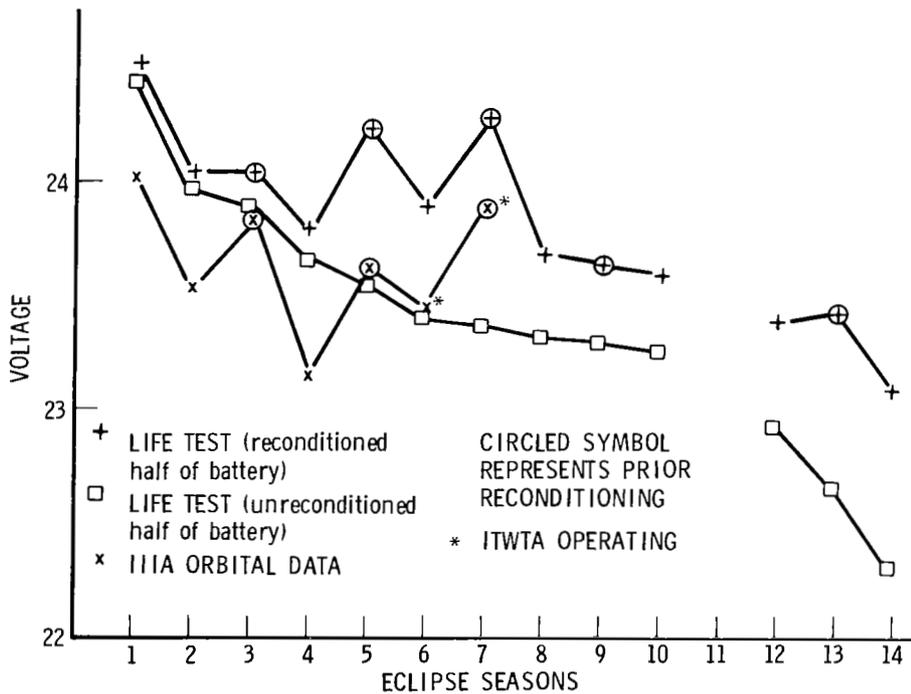


Figure 3-12

# NATO IIIB End of Discharge Voltages

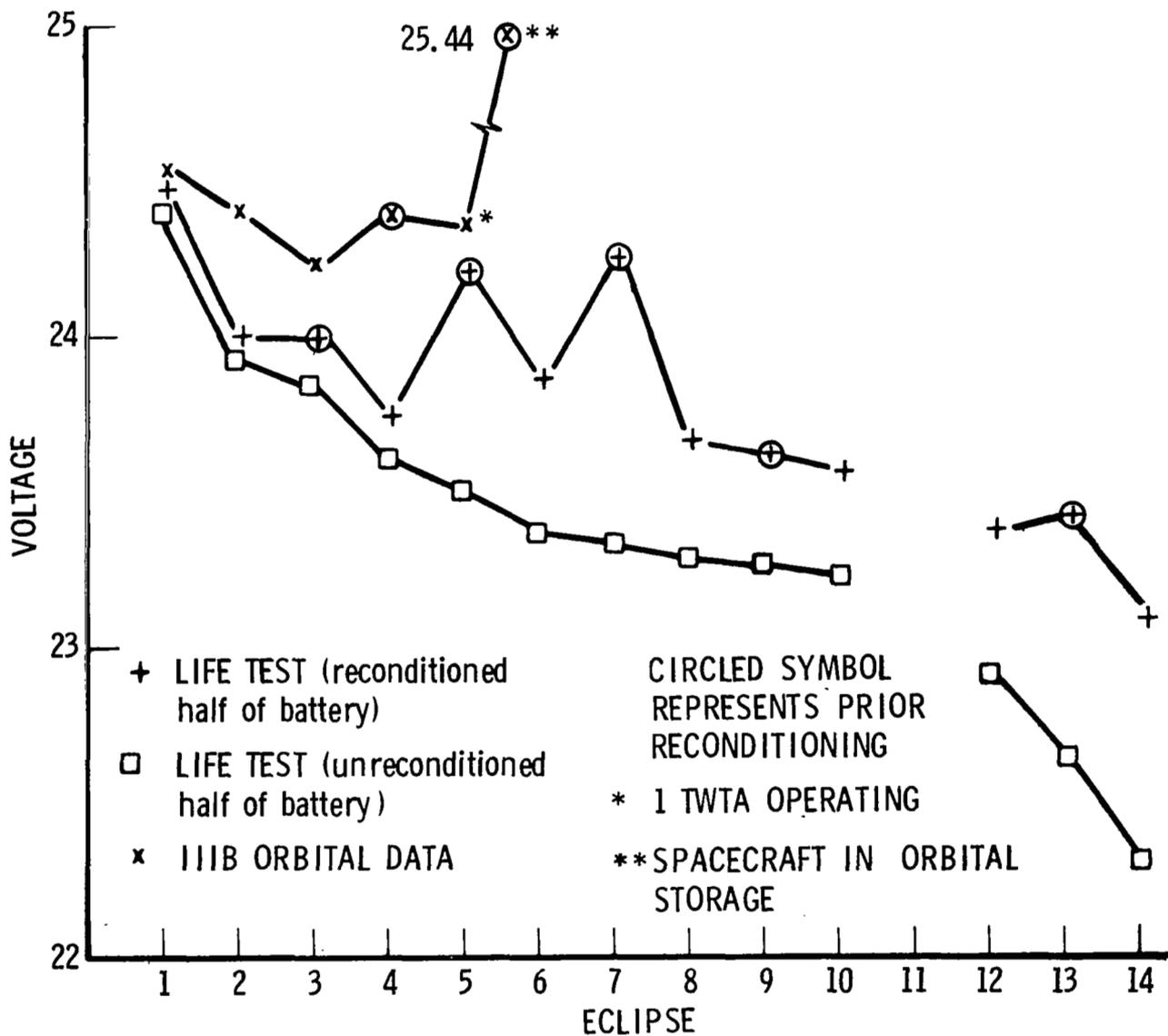


Figure 3-13



## RCA SATCOM-IN-ORBIT EXPERIENCE

P. DeBaylo and S. Gaston  
RCA

About 2 years ago in this battery workshop, there was some data presented by a gentleman from COMSAT, which reflected for batteries that had been reconditioned to say just a little better than 1 volt per cell, we have been limited to shutting off loads after about 5½ years, or eleven eclipse seasons due to battery performance.

This past September at NASA/Lewis, I attended a reliability conference on TWTA's traveling-wave tube amplifiers, where there was strong evidence presented, indicating that TWTA life is being degraded and actually TWTA's are being lost by siphoning on and off.

It appears to me at this point that it is no longer just an inconvenience to our customers and to our users, and so forth, during these eclipse seasons, that we could drop them off, but it was actually now hitting us in the pocket where revenue is going to be lost because we no longer get these TWTA's back on.

This morning I would like to share with you a little bit of our experience that we have experienced in orbit with Satcom and give you a little bit of our test data results.

This morning's presentation will be split into two sections. I will give a little bit of our in-orbit experience, and then Steve Gaston from RCA Astro Electronics will try to answer the question that has been raised many times in the past about where we are going to be 6 years or 8 years into orbit.

I would like to, at this point, thank Dave Stewart, who is with Americom now for doing a lot of the research now and data analysis and development of some of the charts that I am going to present.

(Figure 3-14)

Just as a refresher, I want to highlight a couple of the system characteristics of the Satcom batteries and Satcom power system. The F-1 and F-2 have been in orbit for approximately 4 years. They are seeing either 7½ or 8 eclipse seasons, as of this juncture.

We have essentially three nickel-cadmium 22-cell batteries on board in parallel with independent redundant charges providing the charge rates as you see them. Only on the C/10 charge rate, which we use for reconditioning, do we have any kind of overcharge protection, a B/T-type charge protection system.

Typical temperature range in orbit for the operating periods, where we are actually discharging batteries and charging at the C/20 rates, is shown 2 to 15 degrees average. We do have some peak temperatures during solstice approaching the high 20s.

As I mentioned, we do have onboard reconditioning with individual cell bypasses with 1-ohm resistors. This data has been presented previously in these workshops.

(Figure 3-15)

Here, I have tried to plot out typical battery average minimum discharge voltage. This happened to be battery 3 on the F-1 spacecraft. What this is, is essentially an average data to get rid of some of the telemetry quirks, some of the transients, and so forth, that you see showing in the eight eclipses, minimum voltage about 25.95 volts. Our system requirement is that we must maintain a battery bus of about 25 volts, which is conservative. You might notice that the delta between the sixth and eighth eclipse season is fairly small.

(Figure 3-16)

This is a similar plot for the F-2 spacecraft. Again, it is the same battery looking at battery three on the F-2. The eclipse seasons here are essentially the first complete eclipse season. As indicated before, the F-2 is launched during an eclipse season, so this is really the 1½ eclipse season, if you want to call it that.

A couple of things I would like to point out here. I think the significant thing is that in the last eclipse season we have had a tremendous improvement. If you recall some of the previous workshops, we had indicated that we had a problem in the F-2 spacecraft. We had a blockage which was preventing us from rotating our solar arrays, which is Sun tracking 360 degrees, which required us to go through essentially a reverse slew on a daily basis, and which equates to about a 28-percent DOD on a daily basis.

As of last June this problem went away. It was a self-corrected problem. We were actually able to pass through the same zone and are now operating the spacecraft just like we are F-1. So I would attribute probably some of this improvement here in the seventh eclipse season to the lack of daily cycling at this point.

We also did a double reconditioning in the spring eclipse season for some operational concerns. There was a reconditioning performed after the eclipse season. This might also have contributed to some of the improvement.

I indicated we have a slight load change there, about 1 ampere, which I don't really think is the significant improvement factor here, because you divide that by the three batteries; it is really fairly insignificant.

The F-2 performance, in general, is a little bit worse than that of the F-1, as indicated by the fifth eclipse season data. However, the seventh eclipse season data is significantly improved. So this is something we are going to have to watch and try to figure out what is really happening.

(Figure 3-17)

What I have shown here is essentially the reconditioning-discharge curves for the first, fifth, and eighth eclipse seasons. Now, the question has always been raised, what happens to capacity? We know we have a voltage improvement. From this curve I don't know if I can really answer that question.

The rates here are through a 1-ohm resistor, so it is 1.2-ampere rate decreasing. Also, as we discharge, we have a tendency of warming the batteries because the resistors are mounted to the baseplate of the batteries themselves.

The only thing I can really draw from this particular curve is that things haven't changed. That is what I am really using it for, as a ruler or measurement between the fifth and eighth if reconditioning seasons are essentially identical.

(Figure 3-18)

As to the state of completeness, I have just included the F-2 seventh reconditioning cycle. If you overlay this over the F-2, they are pretty close. We do have a slight softening in the knees on both discharge curves, as would be expected with cycling.

I didn't plot here any of the previous reconditioning because this is the first reconditioning in which we did not have to rewind first. In all the other reconditioning cycles, we did our rewind, which is 28-percent C/2 discharge, and went directly into reconditioning. So, this will be the first real comparison point that we will monitor in the future.

(Figure 3-19)

GASTON: First of all, let me define a little bit better the minimum average cell voltage during eclipse versus number of eclipses. This is what we plotted here. By the minimum average, it is the minimum voltage during the eclipse, most likely at the maximum eclipse time. But it could also be slightly beyond. Average is based on the cell basis, the average cell voltage which we have in the battery.

What we have done is that we compared the top two curves, the Satcom curves, and the bottom three are the Intelsat IV-A data obtained on the cell basis.

Intelsat IV-A is about finished, a little bit more than 12 eclipse seasons, and was supported in last year's power sources when the information was taken from that.

(Figure 3-20)

The next thing we did, we compared and averaged from the previous curve, and we took all three spacecraft and averaged the values. That is the number of eclipse seasons, except in this case it is plotted on the same scale rather than a straight relationship. At the same time we took the Satcom F-1 and F-2 data and combined it, just to get some average number.

Then the third thing we did, we compared it with the Crane tests. We have selected a specific test which happened to be Pack 109, which had about a 60-percent DOD, conducted at 20° C. So, all the triangles here are Crane data.

In the next chart I explain why this one was selected, because it is closest to the DOD characteristics concerned, what the Satcom sees.

Another interesting thing on this Crane test is that the maximum eclipse season, the capacity is measured. By measuring capacity, it is in effect a reconditioning. So what this actually shows is that those data points practically coincide with the Satcom and the Crane tests.

The Crane tests lasted almost 10 years, or twenty eclipse seasons, until it gave out. It is about the minimum voltage which we can tolerate on Satcom, on the stellar base about 1.142, or about nine–eighteen eclipse seasons or 9 years. Since the Satcom tracks that closely with the Crane tests, it appears that that Satcom can perform to minimum voltage for about 9 years.

(Figure 3-21)

This slide compares the designs. It starts out with the Satcom F-1 and F-2 design and has an Intelsat IV design and the Crane test design.

The rated capacity is 12 ampere-hours for the Satcom and 12 ampere-hours in the GE cell, except in Satcom it is actually built in a 10-ampere hour case. Therefore its surface area and the total capacity are less than the regularly rated Crane test. Intelsat is 15 ampere-hours.

Then, we compare the actual DOD of Crane based on either rated capacity or measured capacity. Since the rated capacity is rather a flexible number, depending on what number you like to give, it is a little better indication. When you compare these three depth-of-discharges, they are not that much different. They come relatively close. Based on the rated capacity, it appears that again they are relatively close.

When you come to a current density based on the discharge current, the Satcom current densities are actually somewhat higher than either one of the other two.

The other differences which we have are in the negative electrode. In the Crane test there are no additives; in the Intelsat IV there was a silver additive; and the negative electrode treatment was teflon in the Satcom cell.

The electrolyte is still relatively a close comparison between the Crane test and the Satcom. It was a little bit skimpy as far as electrolyte in the Intelsat IV is concerned.

But each design is different. What I tried to bring out, I want to isolate what are the differences in the designs so we can compare them. But there are also differences in the treatment as far as handling is concerned.

## DISCUSSION

DUNLOP: There are a couple of comments. As far as the negative electrodes are concerned, in the Intelsat IV, there were no additives. We had lithium in the electrolytes, but there was no silver treatment on the Intelsat IV. In the Intelsat IV-A we have a silver treatment.

GASTON: I apologize.

DUNLOP: As far as I know, I think the Intelsat IV battery design and the one that you are referring to on the Crane testing were almost identical.

The other point there I would like to make is that on the Intelsat IV, you showed the data up through twelve eclipses, which is the data that we show. But, if you compare it to the Crane data, you probably should compare it to something more like fourteen eclipse seasons, because on the Intelsat IV you have about 1 year—you have a fair amount of exercising of the battery before the launch. If you take into account all the exercising that is done—in those days we used a battery for all the electrical checkout of the spacecraft, thermal vacuum testing, etc.—if you take that into account, you can actually figure out that your prelaunch—that is your size of the battery—would be equivalent to ½ to 1 year in orbit.

So, if you want to compare it to Crane testing, when you take a battery pack and put it on test right away, you have to make a judgment factor as to how much exercise we put on the battery before it got launched.

I think another point is that when you talked about reconditioning, that was not reconditioning to 1 volt you mentioned, it was reconditioning to 1.15 volts. The difference between reconditioning to 1.15 volts and 1 volt really turns out to be quite significant in terms of the effect it has on the voltage performance.

For example, Intelsat IV-A battery, we do recondition it to 2.0 volt, or slightly less than average, and that battery pack was seeing voltage performance up to nine eclipse seasons. That would be very close to the data that you are talking about for equivalent DOD, about 1.19 volts per cell average after nine to ten eclipses.

GASTON: Yes, but I didn't want to put a judgment factor on it. This is the data as it exists and as it is shown.

DUNLOP: But, to make the comparison, you have to take into account that the battery is 1-year old prior to launch. It has been exercised at least 40 different cycles prior so it is equivalent to at least one or two more eclipses.

GASTON: I agree. But the same is true for the Satcom, and I just don't know what weighting factor to add to that. I didn't go into reconditioning schemes or techniques like it was, let's

say, to 1.15 or 1.0 or 0.5 volts, 0.5 volt like it was a Crane test. I didn't want to go into details because I didn't have enough time.

DUNLOP: I am trying to make a point: That is the results of the Intelsat IV program in which reconditioning to 1.15 volts was practically useless as far as any effect it had on voltage. But reconditioning to something like 1 volt or less has a significant effect, as your data and the data we have on Intelsat IV-A show.

But one point that is a little confusing, is that the failure of the Intelsat-IV cells was not a function of end-of-discharge voltage. What actually started happening on the Intelsat IV cells is that we started running into high-voltage problems or shorting problems.

When we did try to go to deep reconditioning, once we got into those kinds of problems, deep reconditioning really didn't have any further improvement on the batteries.

So the real question we still have as to what the effect of reconditioning is—we know it is pretty well agreed that deep-discharge reconditioning does have a big effect on voltage performance as shown by your data. But, whether it is going to have an impact on lifetime or not is still to be determined.

GASTON: I agree. I am very partial to the individual resistors for each cell draining. This way it cannot reverse itself, and yet you get a good reconditioning.

As far as what the effect on life is, I don't know. The data compared to Crane data gives me some indication that we might expect in 9 years. Until we reach a voltage below that, we might be power limited because of the low-battery voltage. That remains to be proven in time. It's just a prediction.

FORD: Steve, two points: one to be clarified and then I have a statement. What pack number are you looking at at Crane?

GASTON: 209. At 60-percent DOD and run at 20°C.

FORD: 12-ampere-hour cells? I am sure I made this statement before, but I am going to make it again for the record.

All the GE cells that were put on test at Crane prior to 1970—I repeat, prior to approximately 1970—are an entirely different plate design that that we are using today.

GASTON: Yes, I agree. But yet it is the longest test which we had at Crane, and I used it for comparison.

LEAR: Paul, you didn't mention what capacity the cells were that you have on the spacecraft, and how was the power configuration hooked up? Are there three batteries in parallel connected to the bus?

DeBAYLO: Yes. The spacecraft batteries, the 12 ampere-hour, there are three batteries in parallel. All three are required at support mission loads.

GASTON: By the way, the load sharing was very close between the three batteries.

SCOTT: Paul, did I hear you say that in most cases of the data shown, that the batteries were discharged on their normal load before they were put on the resistors for reconditioning discharge?

DeBAYLO: No. What I said was on the F-2 spacecraft when we had to do a daily rewind cycle, which is at 28-percent DOD cycle, the rewind was the first thing done as part of that reconditioning. In other words, we took out the 28 percent and then put them on resistors. The way the F-2 and F-2 spacecraft are now operating, the reconditioning is done from a full battery that has been on trickle charge for about 2 to 3 weeks before we go into the eclipse season. Put on resistors from the initial state.

HALPERT: I would like to ask Jim Dunlop a question, if I may, regarding lithium. You said you had lithium hydroxide in the Intelsat IV and you took it out for IV-A. I wondered why you put it in for IV and took it out for IV-A. Could you briefly discuss that?

DUNLOP: I think it was GE that chose to put it in, not me. We have been trying to figure out ever since, whether we liked it or not. One thing I will say about the addition of lithium hydroxide to the electrolyte, it gives you good low-temperature performance. You get good voltage performance at low temperature.

**BATTERY DESIGN/HISTORY**

**IN ORBIT:** F-1-12/12/75 F-2-3/24/76  
**BATTERY:** Three, 22 Cell NiCd  
**CHARGING:** Normal C/20 -Eclipse Seasons  
 High C/10 -Reconditioning  
 Trickle C/60 -In-Orbit Storage  
**OVERCHARGE PROTECTION:** V/T-Single Curve (C/10 Rate Only)  
**TEMPERATURE:** 2 To 15°C Average  
**RECONDITIONING:** Individual Cell Bypass, To 0.1 V/Cell

Figure 3-14

212

F-2 SPACECRAFT BATTERY 3 AVERAGED MINIMUM DISCHARGE VOLTAGES

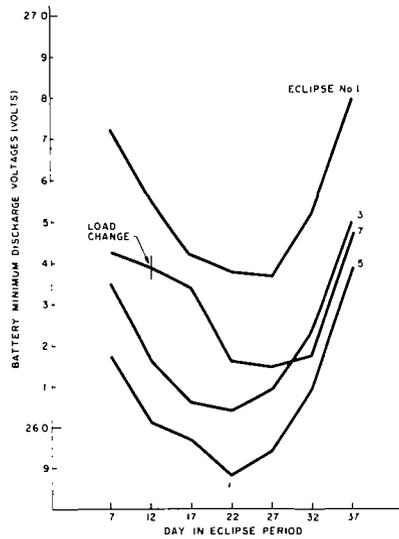


Figure 3-16

F-1 SPACECRAFT BATTERY 3 AVERAGED MINIMUM DISCHARGE VOLTAGE

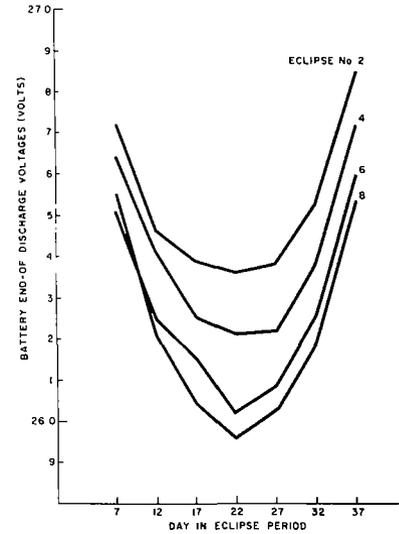


Figure 3-15

F-1 SPACECRAFT BATTERY 1 RECONDITIONING

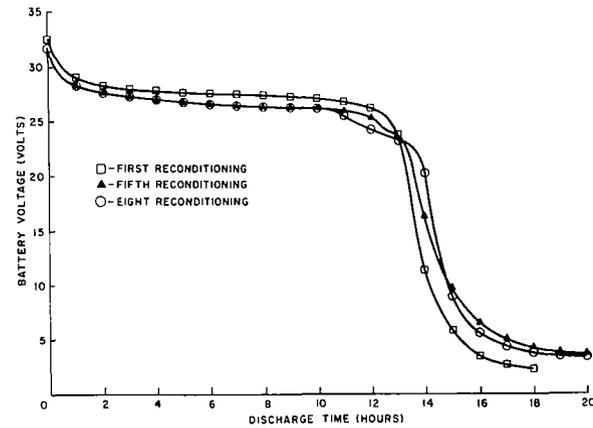


Figure 3-17





## UPDATE OF THE IUE BATTERY IN-FLIGHT PERFORMANCE

S. Tiller  
NASA/GSFC

The data that was presented at the workshop last year summarized performance of the IUE spacecraft batteries from the time of launch, January 1978, through the first 10 months of operation.

(Figure 3-22)

During this session I would like to update the data to carry us through 22 months of operation. First, let me point out that the spacecraft has two 17-cell, 6-ampere-hour nickel-cadmium batteries and that operational directives limit the DOD to 80 percent, and the maximum discharge current to 4.5 amperes per battery. It should also be noted that the two batteries have an approximate 8° C temperature delta between them.

Since launch, the spacecraft has passed through four solar eclipse seasons ranging from 24 to 25 days each. Between the eclipse seasons, or during the solstice seasons, the batteries are placed in a low-rate trickle charge mode of operation.

These curves are plotted from the spacecraft telemetry data with a point selected at random over approximately 625 days of operation. The battery current curves, charge current curves, and the third electrode curves indicate that they are being well maintained in the trickle charge mode of operation.

The fluctuations noted in the battery voltage and the battery temperature are caused by the spacecraft being moved throughout a beta range of 0 to 130 degrees. At 0 and 130 degrees, the solar panels start becoming efficient, and at that time the batteries will start producing power, sending power to the spacecraft.

(Figure 3-23)

This data represents the battery discharge voltage during the peak eclipse seasons, one through four. One thing I would like to point out is that during eclipse seasons three and four, the spacecraft power requirements reduced slightly in order to maintain the batteries above an 80-percent DOD and above a 4.5-ampere discharge current. You can notice this on the third and fourth eclipse seasons, as compared to eclipse season number two.

(Figure 3-24)

Here you see the battery voltage observed at the end of the discharge during the daily seasons or daily eclipse periods over the four eclipse seasons.

Here again you can notice the eclipse season number two and number three, that number two actually has a lower voltage than number three, due to the reduction in spacecraft power during the eclipse season three and four.

(Figure 3-25)

The two dashed lines in this graph represent the rate of battery voltage degradation relative to the available power to the spacecraft, over 14 solar eclipse seasons.

The X's represent the spacecraft batteries, the circles represent data performed on a 6-ampere-hour test pack at Crane, and the lower curve represents data acquired from a test flight tested here at the Goddard Space Flight Center.

This pack has been terminated since we ran the tests through seven solar eclipse seasons. I would like to point out a couple of things:

The pack that was tested at Goddard had been in operation for approximately 1 year prior to the first solar eclipse season at about a 50-percent DOD. After we made some calculations, we believe the battery voltage is approximately 1/4 volt high for this particular data.

The trends being established from these three sources indicate that the spacecraft battery will follow the trend that was predicted on the curve. Future data points from the spacecraft battery and from the tests at Crane will be plotted on the future curves to maintain trends through the future eclipse seasons.

## DISCUSSION

FORD: I might make a comment that the cell design and the background were provided by you in the workshop 2 years ago. Right? Or 3 years ago?

BAER: We went through it a little bit last year, too, but I think it was originally presented 2 years ago.

**IUE SPACECRAFT  
BATTERY TRICKLE CHARGE CHARACTERISTICS  
DURING THE SOLAR SOLSTICE SEASONS  
(BATTERIES SN-05, -06)**

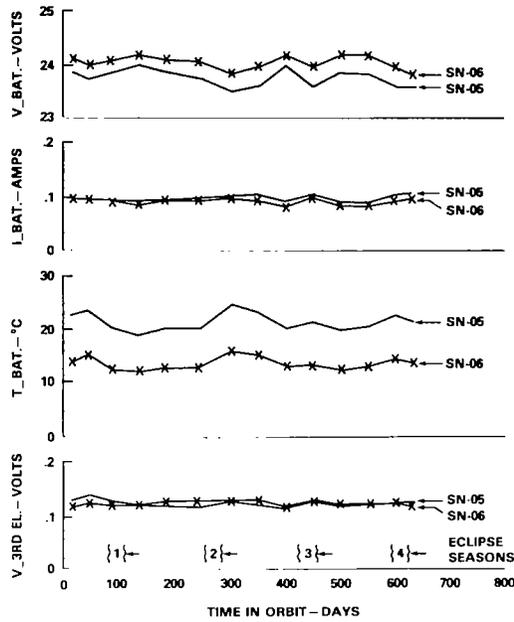


Figure 3-22

**END OF DISCHARGE VOLTAGE VS DAY IN ECLIPSE  
(IUE SPACECRAFT)**

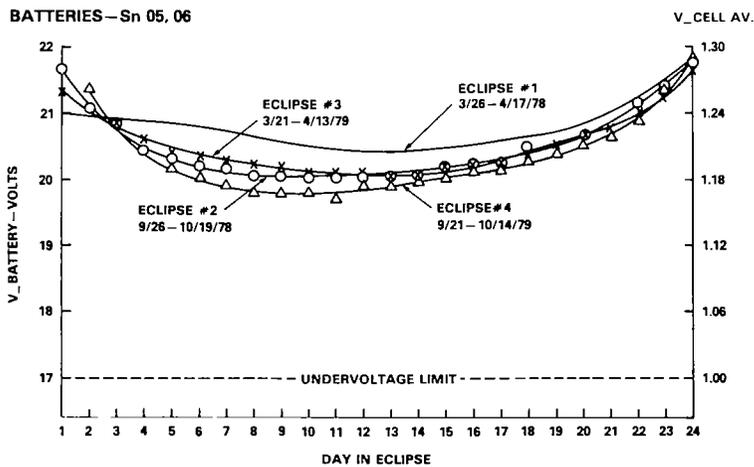


Figure 3-23

### IUE SPACECRAFT BATTERY DISCHARGE VOLTAGE AT THE PEAK ECLIPSE PERIOD OF SOLAR ECLIPSE SEASONS 1-4

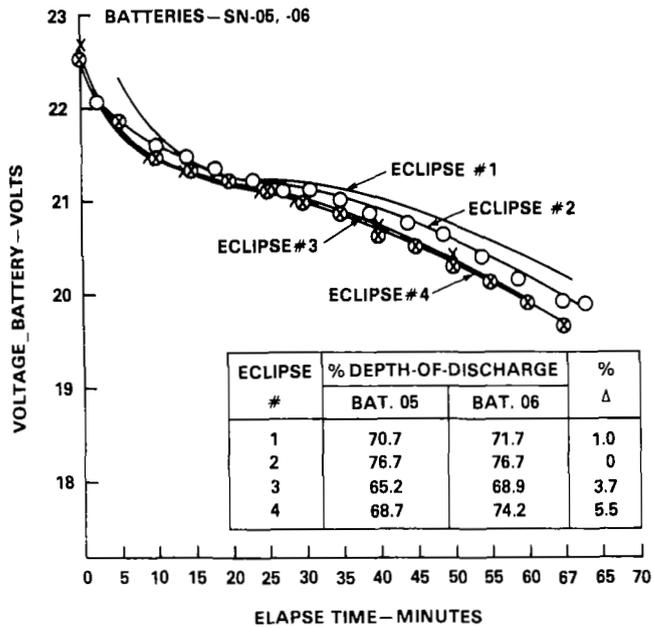


Figure 3-24

### IUE SPACECRAFT BATTERY AVAILABLE POWER AND VOLTAGE VS ECLIPSE SEASONS PREDICTED PERFORMANCE AT 80% D.O.D.

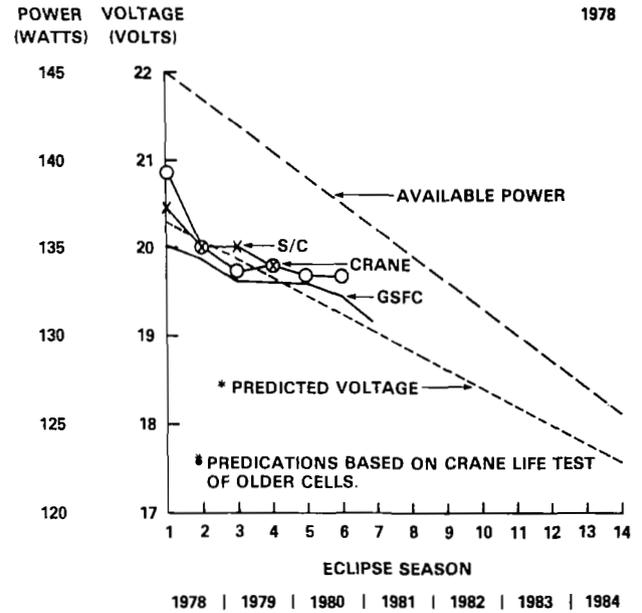


Figure 3-25

## RECONDITIONING OF VIKING LANDER BATTERY

A. Britting  
Martin Marietta

To summarize the previous report we made last year a little bit gives us, if I can use the word, a data base to work from.

(Figure 3-26)

This is a Martin Marietta-built Viking Lander. We launched two of these in August and September 1975 for a 90-day mission to Mars. We were to perform a search for life on Mars, characterize the weather, and do quite a series of other things.

We had a planetary quarantine requirement imposed upon us, in that we were not allowed to contaminate the surface. We interpreted that as meaning we must bake the lander batteries and everything else in it to 233° F for 54 hours. This imposed some interesting hardships for battery designers.

(Figure 3-27)

This is the Viking lander power system. On top are two series connected 35-watt radioisotope thermal electric generators, redundant power conditioning distribution assembly, redundant shunt regulators, and four 24-cell, 8-ampere hour NiCad batteries. The cells were built by GE.

We regulate the bus at 27 to 36 volts. Our battery charging scheme is such that we have a single battery on the charge bus being charged for 1 hour while the other three batteries are supplying the equivalent bus loads. We alternately cycle batteries A, B, C, and D 24 hours a day.

(Figures 3-28 and 3-29)

As I said, the batteries are 24-cell, 8-ampere hour NiCads. We have two batteries for assembly. In the picture on the right you have one battery in the front, second battery in the back. We have two battery assemblies per spacecraft. Each battery weighs 50 1/2 pounds.

Heat sterilization requirement was the item for which we had no data base to draw from so we chose to use Pellon FT 2140 nonwoven polypropylene separator material.

The voltage temperature control for charge conditions was used. During cruise we received power from the orbiter for battery charging at C/15 as well as trickle charging. And the typical lander charge rate was C/8 for all batteries of 1-ampere charger.

During ground testing before launch, we did have individual cell monitoring. But after launch, all we had was voltage and temperature at the battery level.

(Figure 3-30)

On the right-hand side I am putting up the cell characteristics. I will leave them there for your reference.

(Figure 3-31)

This chart represents the battery cycle life from cruise to the present. It gives the typical depths of discharge and the cycles for those depths of discharge. As I said, this was originally a 90-day mission. We are currently passing our 1200th day for both landers, which are still operating.

(Figure 3-32)

We did condition the batteries during cruise. Now that conditioning was done by charging them, discharging them through a 19.3-ohm fix load, and then recharging them, measuring the ampere-hour capacity and recording it.

This is one of the batteries on Viking Lander 1, battery B. During cruise we measured a capacity of 8.8 ampere-hours. We didn't intend to do subsequent tests after landing because we did plan on a 90-day mission. But there was some opportunity here to get some information as far as degradation on the battery is concerned. So we went ahead and reactivated the discharge sequence after 716 days on the surface. We discharged and compared each one of the batteries. This one is representative of the Lander 1 batteries, having roughly a 10-percent degradation after almost 2 years.

(Figure 3-33)

Lander 2 had some interesting differences. This lander tended to operate at a higher temperature than the other lander. We had some spacecraft hardware anomalies that caused it—part of the contribution to the high temperature was a busier sequence, which tended to heat up the equipment bus.

The second curve here was taken just a little bit less than 2 years after touchdown.

What happened here is that during the Martian winter, this particular vehicle happened to sit right on the edge of the northern polar cap on Mars, and therefore we were afraid that frost was going to build up on the landers. As a result, we shut down much of the external operating hardware, such as soil samplers, etc. As a result, the lander was essentially asleep. With it being asleep, we didn't terminate the charge-discharge sequence. We went ahead on a 1-hour charge cycle, but with no discharging, constantly putting power in for 1-hour cycles for roughly the Martian winter, about 6 months.

I think this was partly contributing to the 4.5-ampere hour, or 50-percent loss in capacity that we see here.

(Figure 3-34)

That last slide was about the point to where we had reported last year.

Slightly after the workshop, we got additional data, which showed us the hardware anomaly that caused us to operate in excess of 80°F for the 137-day period. Coupled with low-discharge rates, low-recharge rates, and because of the high temperatures, there was lower battery terminal voltage.

When we came out of this period, we found that we had lost roughly as much as 75-percent original capacity of the batteries. At this time we decided to embark on a program on Lander 2, to do more than just to discharge to the predetermined 27.3-volt cutoff that we had been normally doing earlier along the curve here, and do a time discharge instead.

We arbitrarily chose a 7-hour time discharge through the 19.3-ohm resistive load bank because it fit nicely into the sequence. We followed that by a 21-hour recharge, C/8, and the 19.3 ohms give us a value of C/5 discharge rate. Some of the gains can be seen in the next chart.

(Figure 3-35)

I picked on one battery in particular. I am planning on doing a lot of this testing on all those batteries. I have completed the second battery. This is battery C, but I have completed the second battery already. I will just talk about battery C here.

The second column from the right is the discharge ampere-hours. In there you can see the cruise. And then an early lander capacity being about 10 percent degraded, as was on Lander 1. Then lo and behold, a little over 2 years after touchdown, we see that 75-percent degradation that I talked about because of the thermal and other powers we had there.

We did a discharge shortly thereafter to 27.3 volts. That's a gain of about 1 ampere-hour you see on Sol H58. After that, I started the 7-hour time discharges. Some of what you see on the line is called Sol—Sol is a Martian day and is 24.6 hours long—but on the Sol H65 line, some of that increase you see to the 5.11 ampere-hours is most probably due to the previous discharge test we do where we got 2.95 ampere-hours.

I took that battery down to 9.88 volts, terminal voltage, in the 7-hour period. About 90 days later, I repeated the test to see what impact we had on that battery, gained another 1 1/2 ampere-hours. The battery terminal voltage at the end of that 7-hour period was 18 volts, which has shown that we have done something to the battery.

(Figure 3-36)

This vugraph is rather a dramatic one. It is a graphical presentation of the previous chart.

This curve summarizes all of what was on the last chart. The highest curve, the long-dashed curve there, happens to be the cruise curve. You can see the subsequent degradations in capacity finding the long-time discharge. The first one is the thin solid line going down, the 9.88 volts. On the final-time discharge we see what may even be an evidence of second plateau. I have marked on that final curve the 27.3-volt power conditioning distributions, where the cutoff level would be.

(Figure 3-37)

Currently, we are on about a once-a-week basis on Lander 1, running a sequence that discharges the batteries about 1 ampere, or at about 12-percent DOD. Peak discharges may reach 15 percent. We are recharging at about a 1-ampere rate.

Currently, on the batteries on Lander 1, we have run approximately 7000 cycles at less than 10-percent DOD. On Lander 1, because we have been running fairly deep discharges before this time, I believe they are semiconditioning the batteries. We have had no evidence of any battery degradation.

The battery open-circuit voltage remains as it was at touchdown, at 32 to 33 volts. We are having equal load sharing to within 1/10 ampere during all heavy or light discharges. Sharing very well. And our batteries are reaching charge cutoff on recycle.

(Figure 3-38)

As I said, we had to work with Lander 2 a little bit. It is going through about a once-a-month 1- to 1.3-hour discharge at 12 to 15 percent, at a discharge of 18 percent maximum.

I am going to complete our 7-hour time discharges. I have worked on battery A and battery C so far, and batteries B and D this month and next month. Subsequent to that I will report on them. I do plan on finishing at least one time discharge in every battery.

Since we began the discharge, 7-hour time discharges, we have got a significant increase in battery capacity. The open-circuit voltage recovery on the Lander 2 batteries, which was 32 and 31 volts, is now back up to 32 to 33 volts.

Batteries A and C, which are already exposed to the time discharge, now take more than their share of the load. There is a 4-ampere load on the bus. That's like three-quarters of it. The third battery on the discharge bus hardly supplies any of the load. And we are reaching regular battery charge cutoffs.

(Figure 3-39)

In summation, we have done approximately 4 years of operation on the surface, but I have to say no failures with quotes around it. We did have only 90-day operational requirement. Our polypropylene separator material chosen appears to be still working well. He might want to add a couple of things to that.

One of the things we did learn here was that although we didn't plan on having any reconditioning mechanism on the spacecraft, in this case it was good that we did. We think we have learned something from that. But in future missions of this type, it might be wise to always include something to enable you to do some kind of conditioning.

They might be good, so we don't do time discharges and worry about cell reversals. As you are taking the batteries down, you might want to have some individual cell monitoring. I think that's probably a good idea.

Our current plans now are for Lander 1 and Lander 2: Lander 1 is going to operate until 1990. I am not going to stick around and monitor it that long. Lander 2, as somebody mentioned, doesn't have any TWTA problems. We lost both TWTA's, we lost each of the TWTA's on Lander 2, so we only have relay length capability from Viking Lander to Viking Orbiter which then gets relayed to earth.

When the last remaining two Orbiters go away, they run out of control system gas, that will be the end of the Viking Lander 2 mission. That is why I am working heavily with Lander 2. I feel that's my vehicle that I can play with a little bit. I call it my billion-dollar playtoy and try to gather as much information before we lose that vehicle.

In a recent slide taken on the Martian surface from Lander 2 the temperature was about  $-154^{\circ}$  F during the day and  $-196^{\circ}$  F at night. There is frost on the surface. That's what is called a clathrate. It is composed of six parts carbon dioxide and one part water vapor.

## DISCUSSION

MUELLER: How many cycles did you get within one cycle per day?

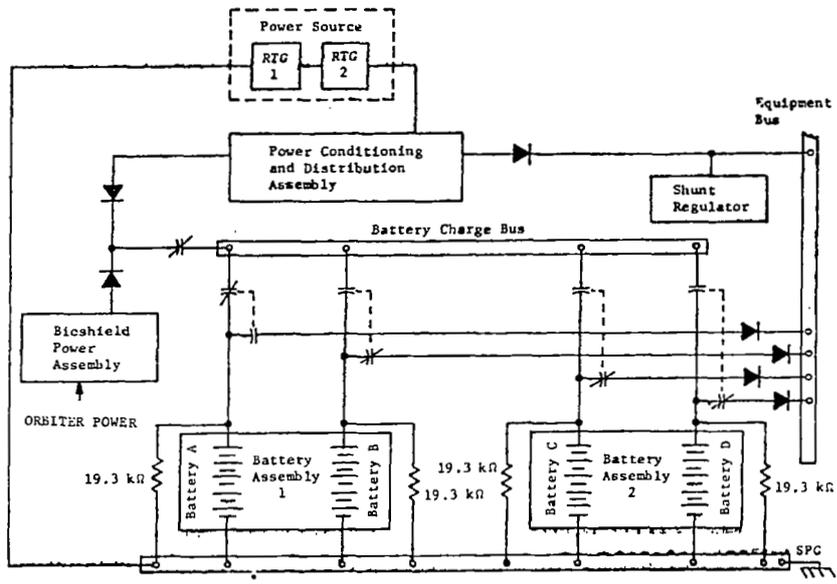
BRITTING: When you say cycles, charge cycles on batteries?

MUELLER: Current discharge cycles.

BRITTING: We charge the batteries on a once-per-hour basis essentially six times a day. Each battery is on the bus 1 hour a day—on the charge bus, 1 hour; then on the discharge or equipment bus, 3 hours. Then back on the charge bus for 1 hour.

MUELLER: Six cycles per day?

BRITTING: Six cycles per day.



Viking Lander Power System Block Diagram

Figure 3-26

Viking 75  
Mars  
Lander

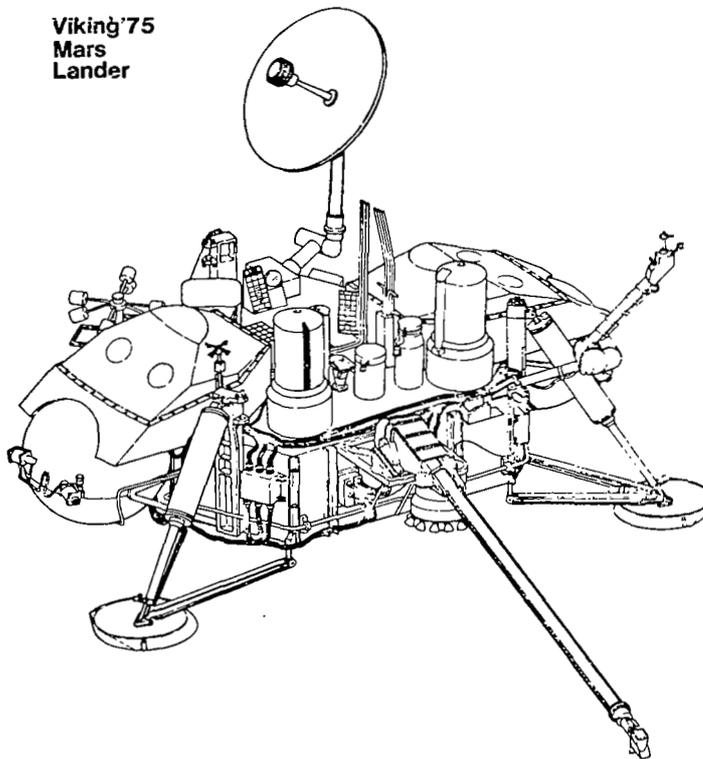


Figure 3-27

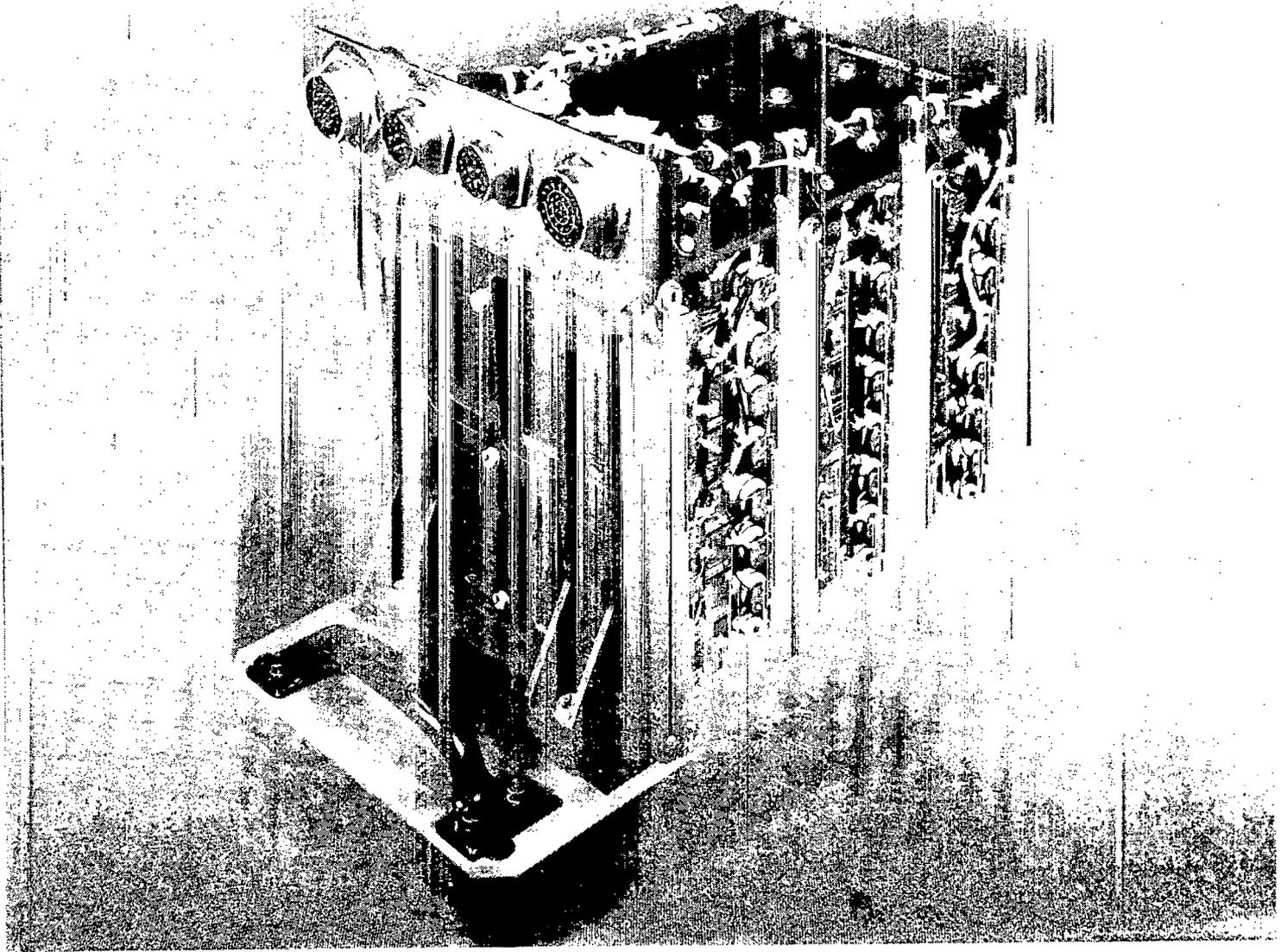


Figure 3-28

## BATTERY CHARACTERISTICS

2 - 24-8AH BATTERIES/ASSEMBLY

2 - BATTERY ASSEMBLIES/SPACECRAFT

BATTERY WEIGHT 50.5 LBS

HEAT STERILIZATION 54 HOURS @ 233°F

CHARGE CONDITIONS

VOLTAGE/TEMPERATURE CONTROL

C/15 - IN CRUISE FROM VO 75

C/160 - TRICKLE

C/8 - TYPICAL LANDED OPERATION

MONITORING

TEMPERATURE	}	FLIGHT
BATTERY VOLTAGE		
CELL VOLTAGE - GROUND ONLY		

Figure 3-29

Cell Capacity	8 A-h (Rated)
Cell Weight	273 gm - Lot Average
Cell Size	7.589 cm x 2.27 cm x 8.651 cm (including terminals)
Case Material	304L Stainless Steel
Case Wall Thickness	0.48 ± 0.05 mm
Insulated Terminals	Positive and Negative
Terminal Type	Nickel Post with Ceramic Insulator CE - all Nickel-Braze
Auxiliary Electrode	None
Separator Material	Pellon FT2140 Nonwoven Polypropylene
Separator Thickness	0.216 mm
Plate Pack Wrap	Pellon FT2140 Nonwoven Polypropylene
Case Liner	0.127 mm Solid Polypropylene Sheet
Electrolyte	KOH
Electrolyte Concentration	34%
Electrolyte Quantity	21.5 to 23.5 cc
Plate Substrate	0.101 mm Perforated Steel Sheet
Sinter Porosity	80% Nominal
Number of Plates	POS 11 NEG 12
Plate Size	7.0 ± 0.03 x 4.9 ± 0.03 cm
Plate Thickness	POS 0.066 to 0.071 cm NEG 0.078 to 0.081 cm

Figure 3-30

Period	BATTERY CYCLE LIFE			
	VL-1	DOD	VL-2	DOD
<b>Cruise</b>				
Cruise Checkout	1	25%	1	25%
Subsystem Test	6	20%	6	20%
<b>Mars Orbit Insertion</b>				
Preseparation Checkout	1	25%	1	25%
<b>Preseparation</b>				
Preseparation thru Touchdown	1	50%	1	46%
<b>Landed</b>				
Thru end of Primary Mission Sept 76	43	55% Max 10-20% Typ	61 Nov 76	29% Max 10-20% Typ
Thru Conjunction	Nov 76 65	23% Max 13-20% Typ	8	5% Max 5% Typ
Thru Extended Mission	Jun 78 308	40% Max 10-20% Typ	211	42% Max 10-20% Typ
Thru Nov 78	32	15% Max 5-10% Typ	8	20% Max 10-20% Max
Thru Continuation Mission	Mar 79 32	15% Max 5-10% Typ	2	22% Max 12-20% Typ
Thru Survey Mission	Oct 79 18	15% Max 5-10% Typ	4	20% Max 12-18% Typ
<b>Total</b>	<b>507 Cycles</b>		<b>303 Cycles</b>	

Figure 3-31

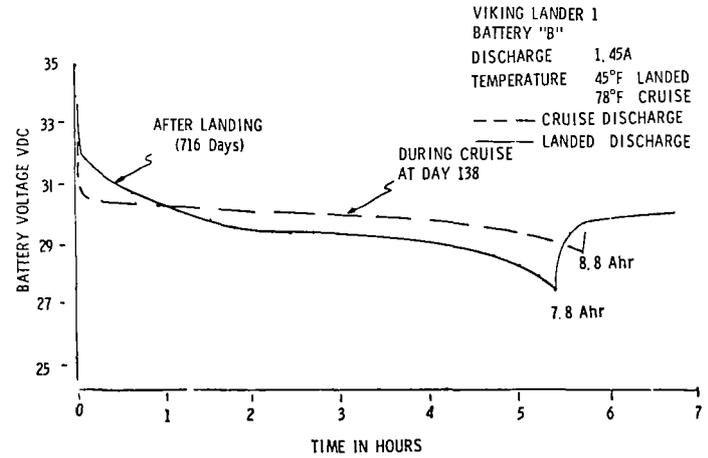


Figure 3-32

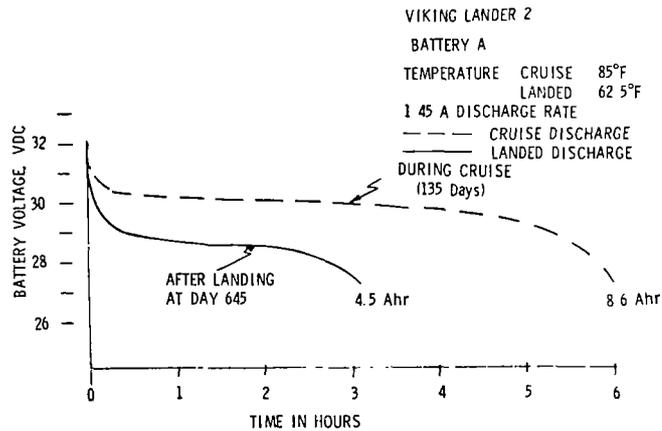


Figure 3-33

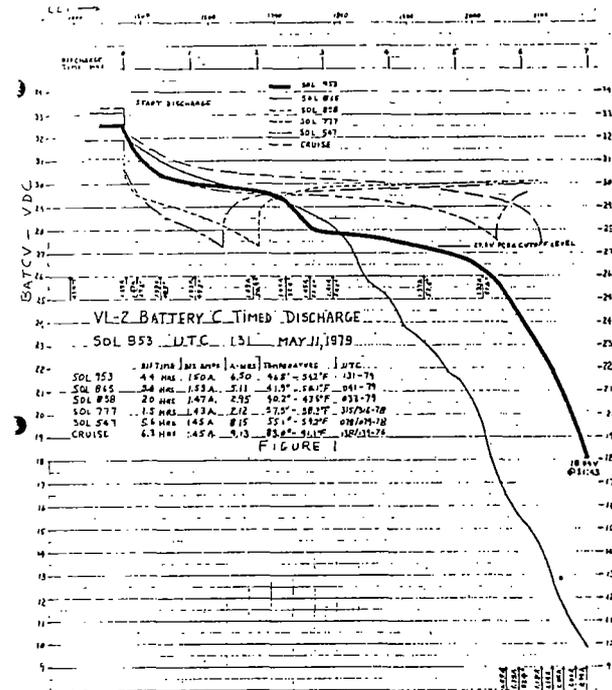


Figure 3-34

<u>PERIOD</u>	<u>UTC DATE</u>	<u>DISCHARGE DURATION (HRS)</u>	<u>AVERAGE DISCHARGE VOLTAGE (VOLTS)</u>	<u>DISCHARGE AMPERE-HOURS (AH)</u>	<u>DISCHARGE TEMPERATURE (°F)</u>
CRUISE	138/139-76	6.3	30.2	9.13	83.0° - 91.1°
SOL 547	078/079-78	5.6	29.4	8.15	55.1° - 59.2°
SOL 777	315/316-78	1.5	28.7	2.12	57.5° - 58.3°
SOL 858	033 - 79	2.0	28.9	2.95	40.2° - 43.5°
SOL 865	041 - 79	3.42	29.95*	5.11*	41.9° - 50.1°
		7.0	24.78**	8.74**	
SOL 953	131 - 79	4.35	29.37*	6.50*	46.8° - 54.2°
		7.0	27.66***	9.84***	

\* To 27.3 V nominal PCDA charge control logic cutoff level

\*\*

\*\* To 7 hour timed discharge. Battery terminal voltage at this time was 9.88 volts.

\*\*\* To 7 hour timed discharge. Battery terminal voltage at this time was 18.04 volts.

Figure 3-35

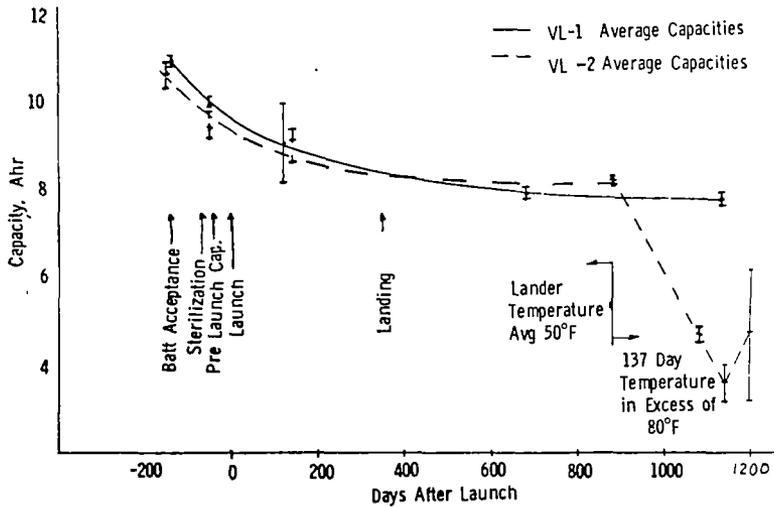


Figure 3-36

PERFORMANCE (CONT)

VIKING LANDER 2

- o DISCHARGE/RECHARGE
  - 1 AMPERE DISCHARGE (C/8) FOR 1-1.3 HOUR APPROXIMATELY ONCE/MONTH (12 - 15% DOD)
  - PEAK DISCHARGES TO 18%
  - 7 HOUR TIMED DISCHARGE AT APPROXIMATELY ONCE/ YEAR THROUGH 19.3 OHM FIXED LOAD BANK
- o RESULTS
  - SIGNIFICANT INCREASE IN BATTERY CAPACITY
  - BATTERY OCV WELL RECOVERED FROM 30-31 VDC LOWS TO MORE CONSISTENT 32-33 VDC
  - TWO BATTERIES ALREADY EXPOSED TO TIMED DISCHARGE HOG DISCHARGE LOADS FOR LONGER PERIODS OF TIME
  - REGULAR BATTERY CHARGE CUTOFFS

Figure 3-38

PERFORMANCE

VIKING LANDER 1

- o DISCHARGE/RECHARGE
  - 1 AMPERE DISCHARGE (C/8) FOR 1 HOUR  $\approx$  ONCE/WEEK (12% DOD)
  - PEAK DISCHARGES TO 15%
  - RECHARGE @ C/8 RATE
- o RESULTS
  - NO EVIDENCE OF BATTERY DEGRADATION
  - BATTERY OCV REMAINS AT 32-33 VDC AFTER 4 YEARS
  - EQUAL LOAD SHARING EVIDENCED DURING DISCHARGES
  - BATTERY CHARGE CUTOFFS OCCUR EACH HOUR

Figure 3-37

SUMMARY

- o 4 YEAR OPERATION WITH NO FAILURES
  - 90 DAY OPERATIONAL REQUIREMENT
- o CELL TYPE
  - POLYPROPYLENE SEPARATOR
  - STANDARD UNTREATED NEGATIVE PLATES
  - HEAT TREATMENT OF COMPLETED CELL ASSEMBLY
- o RECONDITIONING /MAINTENANCE VERY SUCCESSFUL
  - VIKING LANDER-1 WEEKLY DISCHARGE/RECHARGE
  - VIKING LANDER-2 TIMED DISCHARGE/RECHARGE RECONDITIONING

Figure 3-39



## DISCUSSION OF THE SAGE ANOMALY

D. Baer  
NASA/GSFC

We could also call this the demise of a battery. Two almost identical spacecraft are HCMM and SAGE. They both have cells from the same manufacturing lot. It was an Eagle Picher 9-ampere hour cell. Eagle Picher was also the battery manufacturer, and Boeing was the prime contractor.

SAGE was selected for this presentation because it had the most severe and the most rapid degradation, plus it was documented a little better because it had a tape recorder on board, and HCMM did not.

(Figure 3-40)

This will give you a little bit of background. Here is a block diagram of the power system. It's a two-panel solar array that can be rotated plus or minus 80 degrees about the spacecraft X-axis, plus X is the velocity direction of the spacecraft.

The main bus voltage was specified at 28 plus or minus 4 volts, and the regulator bus was 28 volts plus or minus a percent. The loads are connected through a relay box for both the instrument module and the space module loads. There is undervoltage detector set at 23.5 volts and also an overload sensor.

There were some thermostats on the battery for overtemperature, and they were set at 33 plus or minus 2 degrees, although actually we ended up a little higher, something like 38 degrees where they tripped it. When they were tripped, they forced the battery to go to voltage level. It is a temperature compensated voltage limit, charge control and there were two limiters. The battery was 21 series connector cells divided into three packs.

(Figure 3-41)

This vugraph shows the voltage levels. The two limiters worked in tandem. The way it worked, when the voltage came up, the level B would clamp. When those transistors began to saturate at about 4 amperes, then the voltage would be clamped at the A limiter, at the higher curve.

These curves are very similar to the curves used in the MMS spacecraft, or in the standard battery spec. The A limiter is level 6. They are the same curves. The only difference between these is a little bit more space between the AEM voltage limits, about levels 5 and levels 6.

(Figure 3-42)

Here's a little more background. This curve shows the same SAGE sunlight duration, and you can see how it varies. Sunlight duration is as little as 61 minutes and as much as 97 minutes, which is the orbit period.

The spacecraft is in full sunlight every couple of months from 7 to 10 days. For most part, it is between 61- and 70-minute sunlight duration. However, the solar arrays are now illuminated when the spacecraft is in the sunlight, which may be another 10 minutes or so before the solar arrays are illuminated.

Therefore, the battery discharge periods can be as long as 59 minutes—45 minutes full loads, and load shares with solar array for about 14 minutes. So that only allows 38 minutes for charging. This and the HCMM spacecraft are the only spacecraft I am aware of that have a longer discharge period than they do a sunlight period.

(Figure 3-43)

This vugraph shows the beta angle, which is the angle the Sun makes when normal to the orbital plane. That is what determines the sunlight duration.

Here are battery average dissipation and battery temperatures, which are the diamonds and the squares. The circles are the panel 1 temperature, which is where the battery is mounted.

Through the first 800 orbits, the solar input was pretty much due to the variation because the battery dissipation was over 5 watts. But one part was under 5 watts. As you can see, at beta of 90 degrees when you have the longest arc period, the batteries are coolest. When the sunlight period is increased, then the temperature comes up.

But around orbit 800 or a little bit after, you can see some changes starting to take place. That is a delta between the battery panels, and the battery temperatures are beginning to increase along with the battery dissipation. And that is when the problems started to occur. That will probably be illustrated in some of the later vugraphs.

(Figure 3-44)

This is the percent recharge versus orbit. It varied anywhere from 95 percent to about 104 percent through the first 800 orbits, or slightly after 800. Then they began to climb.

Even though the voltage on the level was lower, it went from 7 to 6, then 5, 4, and then 5 again. The first undervoltage occurred on orbit 1277 right after this data point was taken. These data points are full orbit per course, so we don't have it every orbit.

Even though we were recharging batteries about 112 percent, we still have that undervoltage condition. After that point, the temperatures really started to take off as well as the percent return.

(Figure 3-45)

This vugraph is a typical early orbit where we had a 38-minute charge period and 59-minute discharge period, which resulted in a 21-percent DOD.

If you notice, we had only a 95-percent return when we were at level 7. We had the main bus voltage that is relatively flat until it reaches a clamp. The battery is running fairly cold, around 8 degrees. There isn't much of a delta between the panel and the battery pack.

There is a nice taper on the charge current. These humps are when the experiment is on, and it is being used. I will just move this slide over here so you can take a look at it, and I will show you one of the later orbits.

(Figure 3-46)

As you can see, there have been quite a bit of changes. On this one the DOD is a little lighter; it's a little shorter dark period. We are only running 19 percent, but it is 157-percent recharge, even though at this one we are at level 6.

If you notice the discharge voltage profile, this is dipping down to 24.8 volts, where on the early orbit 59596. The end-of-discharge was a little above 26 volts. The charge profiles also changed where the charge voltage seems to follow the charging current.

The battery temperature is now decreasing during discharge, and when we get to the over-charge region, there is a rapid increase in battery temperature. Battery temperature is now up in the neighborhood of 25 to 26 degrees.

There is a big delta between the panel 1 temperature and the battery pack temperatures. There is a very little taper where it drops off here. It is solar array limited. This was the last full orbit record we could get. The next time we tried, it was around orbit 1685, and we get undervoltage after about 127 ampere-hours out.

We continued bouncing around between 100 voltages and high battery temperatures by playing with the charge voltage limit until about over 2110 and 2120 when two cells, apparently, shorted.

At this point the voltage would no longer come up to level 1, so we could no longer use the charge control, the voltage limiter charge control. So the only charge control we had left was to rotate the arrays and try to limit the amount of current going into the battery in that fashion.

Also, we had to disconnect the intervoltage circuit, and the only indication we had of low voltage was when the clock stopped. The spacecraft clock was stopped at around 26 volts.

We are still operating. We are up to orbit 4000 continuous Sun now. We are not taking any signs. But I estimate the capacity of the battery is now in the neighborhood of 0.9 ampere-hour. And there was another cell shorted at orbit 2530.

(Figure 3-47)

This is rather an interesting curve. This is kind of Sid Gross' idea. He started to plot this on HCMM. This is what I call a zero-current voltage. This is at the transition point between charge and discharge. When you get on the edge of the orbiter records, you take a voltage point.

See, early in life if anything, it was going up. Then there again, around orbit 800 it started to fall off a little bit. Then, by orbit 900, it was downhill and never really recovered.

Back in here we are playing around with the different voltage limits, and it had a little bit of effect, but not very much.

(Figure 3-48)

We did some teardown analysis. These pictures are from a cell that was torn down after 2264 cycles. These results were very similar to a cell that was opened after about 2 years of tests at Crane. What I want to point out here is the way the separator is sticking to the neck of the plate.

When the cell was opened and we tried to get the separator off, it just kind of layered. And what would happen, one-half would stick to the plate, and the other half would come into your hand. Even when we went to the SOXIC extraction, we still couldn't get the separator off the negative plate.

(Figure 3-49)

I am not going to go over this whole chart. Since some of the analysis work was done, a little bit of clarification is needed.

Lot 1 on HCMM was flown on both spacecraft. On the SAGE lot, as you recall last year, Floyd made a presentation of some of the test data we got on the ground. The SAGE performance was so poor that we decided not to fly it. But, since they are both supposedly made the same, it is good for comparison.

As you can see, there is some plate expansion, both positive and negative. This first column is uncycled cells, and the other one is after 2 years of tests. The negative utilization isn't too good, about 55 percent in this particular cell, anyway.

I think what is important is the carbonate content of the uncycled cell. This is in percent mil equivalent of potassium carbonate in the electrolyte. A little different way than we usually report it.

To give you an idea, 31 percent is rather high, maybe just a little bit high for a cell to cycle like this—58 percent, and 52 percent, and 48 percent are very high numbers.

What we concluded to date is that the anomaly is essentially a bunch of soft shorts which is probably caused by cadmium vibration, and in some cases soft shorts developing hard shorts, we have lost three cells.

Why it happened so quickly results in several debates and discussion: Perhaps high carbonate content across it, plate expansion, heavy loading, or maybe a combination of several things.

I might want to add that the problem did not show up in any ground tests. The cells have flown and they look fine. Although there was quite a bit of voltage diversion on charge and discharge and it was a little hard to control the percent of return, the cells on test at Crane did not show a great deal of capacity loss after a 2-year capacity check.

This is rather from memory, but it was something on the order of 7.5- or 8-ampere hours. So it wasn't too terrible. These cells were also bought to the 1974 15,000 spec or a similar type of spec.

## DISCUSSION

MILLER: Dave, I am sure you are aware that NASA was kind enough to furnish us the reports, data, and analysis of your efforts in this problem. I guess probably we, better than anybody else, really appreciate just how much work you guys did in this area, and I think you should be commended on this. I would like to take this opportunity to do that.

We also appreciate your suggestions with respect to our manufacturing changes that you have brought out. In the paper we will present tomorrow, we will cover some of these areas. Using this data, we had several meetings back at Eagle Picher to see what we could contribute to the investigation.

Although we are certainly not impartial observers in this matter, we probably look at your data from the respect of trying to defend the matter. However, I think there were some valid questions brought up in our meetings. When we looked at the thermal design of the spacecraft, we noticed several comments in the reports. The thermal environment of the battery was very marginal in the thermal design so that some equipment would have to be turned off and equipment would have to be used at different times to stop from overloading, evaluating the cause of the thermal problem.

We noticed that as the battery was just approaching its maximum thermal input from the Sun, as the vehicle rotated and the Sun was shining directly on the panel to which the battery was mounted, there was a decision to go to a higher voltage cutoff level, which may not have been a really appropriate way to use the battery. There was also apparently a thermal abnormality associated with some adjacent panels on the batteries prior to battery mount.

We looked at the carbonate which you pointed out in there. If you would back those figures back to the specification level, you will find that 40 or 50 percent level as you expressed it in milliequivalents for actual free hydroxide ions. That translates into less than 2 percent carbonate per plate weight, and that was the specification limit for the program.

If you looked at some of the thermal data on there, as I am sure everyone realizes, the HCMM/SAGE battery is not really a 21-cell battery. It is three 7-cell batteries, and they are physically separated. However, the two battery temperature profiles track very well.

The problems you perceive are cell problems, let's say, individual cell problems and still allow these two values to subtract --

I guess I won't take up any more time of your meeting, but I think there is sufficient evidence to indicate that batteries shouldn't take full blame. I think there are some areas and some questions to be answered, and let me just stop there.

BAER: You brought up several points, and I will try to address them, if I can remember them.

I think thermal design did leave something to be desired, and certainly contributed after the problem developed into making it hard to control. Because with the 5-watt design for battery thermal dissipation, we could dissipate slightly more than that during the longer eclipses, just in the eclipse part. So that allowed nothing for recharge. It should have run a little warmer than what was predicted anyway. However, I wouldn't expect to be able to control this by using a different voltage level which we tried.

In regard to your comment about going to level 7, that was done because on one of the previous orbits, we weren't getting a full-percent return in the spacecraft. So we went to level 7 for a while. At that point in the game the thing was running cool, and we were worried about the battery running down.

If you looked at the one chart I read up there, the orbit 596, we had only 95-percent return.

To back that up, the temperature didn't rise at all during the charge period. So that certainly indicated that at a beta 90 during the longer dark periods, you were not getting the batteries fully charged. You weren't in energy belts.

So we did go to level 7 for a few orbits, and when we knew the dark periods were getting shorter again, then we went back to our level 6.

As far as the carbonate is concerned, I would have to pass my comment on that to Pat Montgomery, who is here today. I don't think Jerry has anything.

HALPERT: That was percent there, not milliequivalents, right?

BAER: Right. It was percent. Well, percent milliequivalents.

THIERFELDER: Dave, you showed a photograph and commented that the separator was sticking to the negative plate. What cells were they? Did you open other cells where it wasn't sticking? What point in life did the sticking to the negative plate start?

BAER: Well, it is rather like comparing apples and oranges. That was not the plate lot. That was after 2264 cycles of tests here on the SAGE lot cells. There were two cells opened. There was usually some dryness and a little bit of sticking. That was the most severe case of sticking.

THIERFELDER: At 2000 cycles they were sticking?

BAER: On that particular cell.

THIERFELDER: You don't have any number where they were not sticking?

BAER: As I said, some of the ones at about 2000 cycles weren't sticking very bad at all, just a little bit more of a dryness than a sticking.

LEAR: You had reference to the photographs, the sticking of the separator. What about positive plates, did you notice any of the bubbling or crystalizing?

BAER: On the positive plates, you could see they looked as if they were under pressure and they were starting to deteriorate a little bit. I am addressing strictly the flight lot cells, the one that was opened at 10,000 cycles. So there was a little bit discoloration. It looked as if it had been under pressure.

WEBB: Was there a plate hold down or constraint?

BAER: I don't remember. Lee, do you remember?

MILLER: There's no hold down in the cell.



## SAGE SUNLIGHT DURATION VERSUS DATE

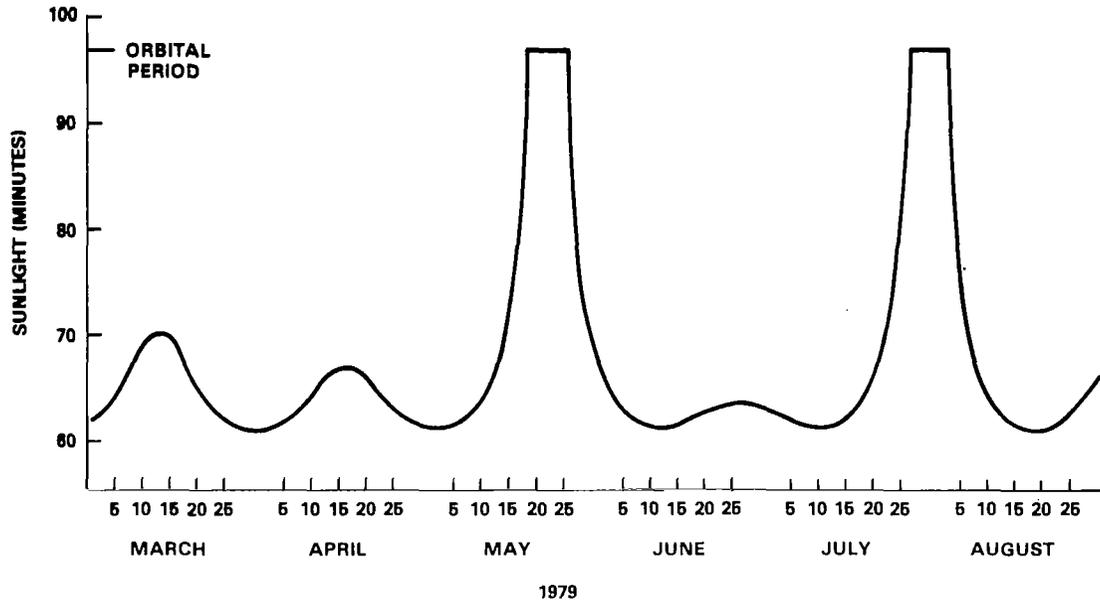


Figure 3-42

## SAGE BATTERY TEMPS

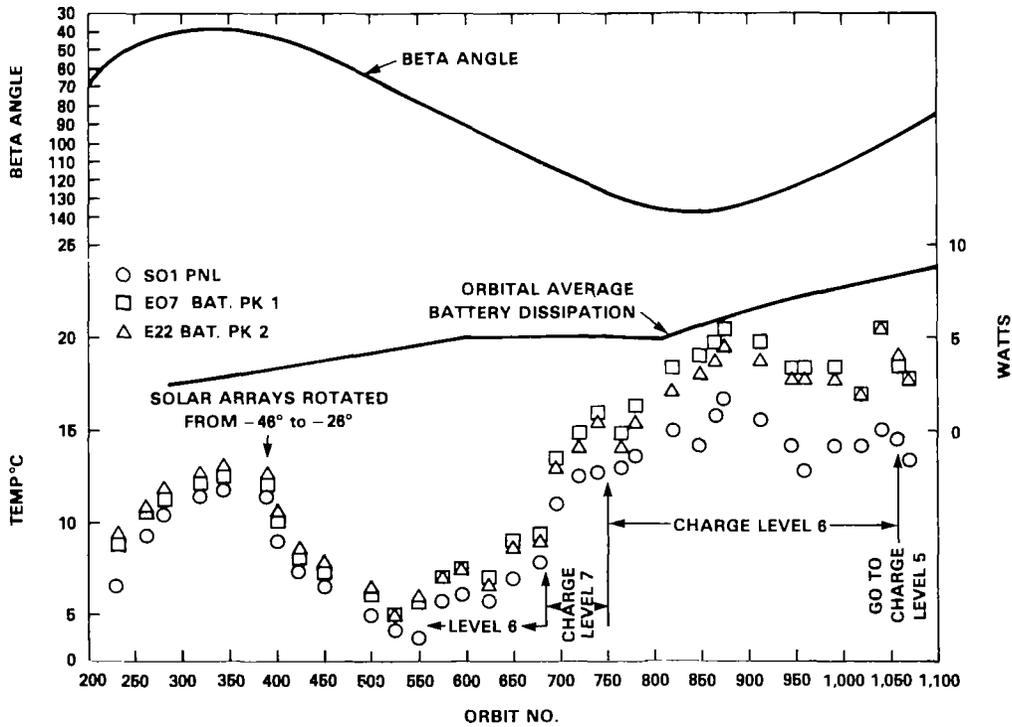


Figure 3-43

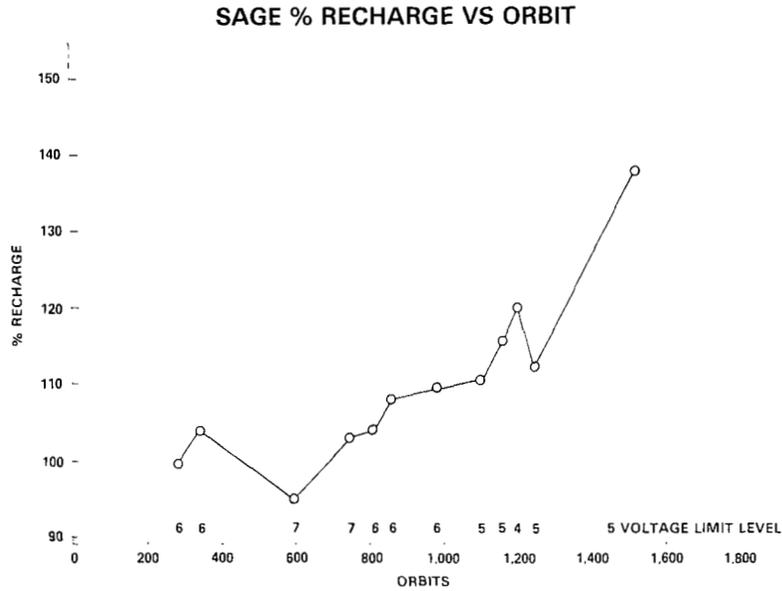


Figure 3-44

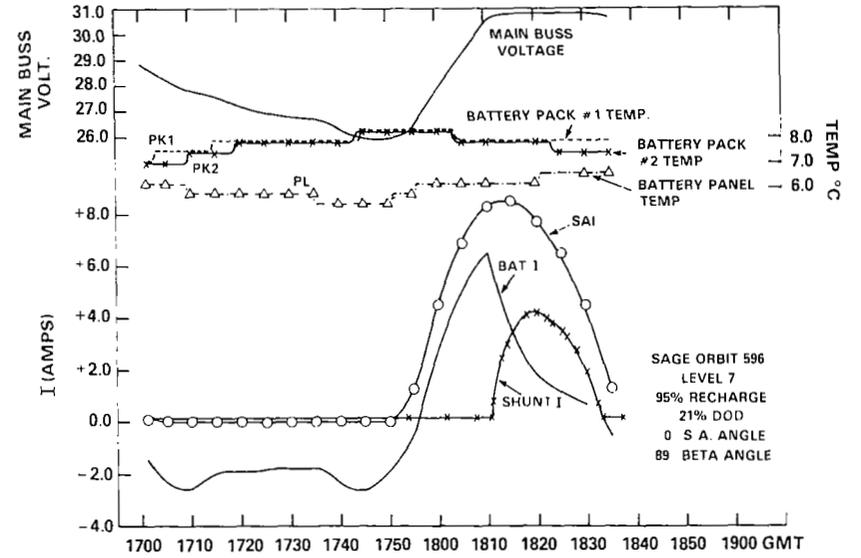


Figure 3-45

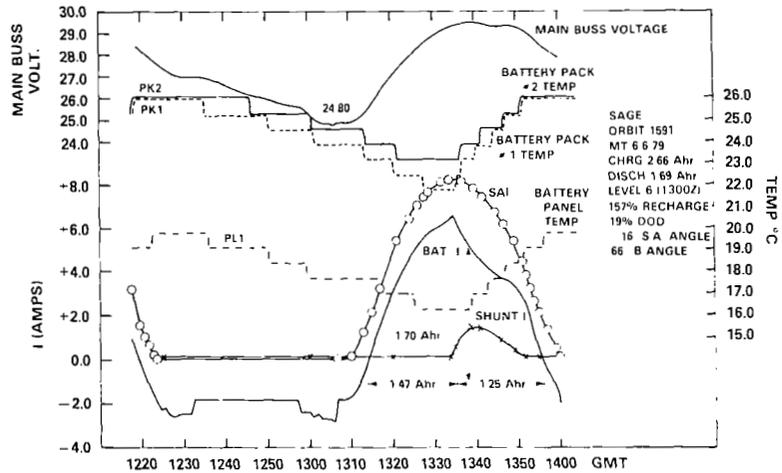


Figure 3-46

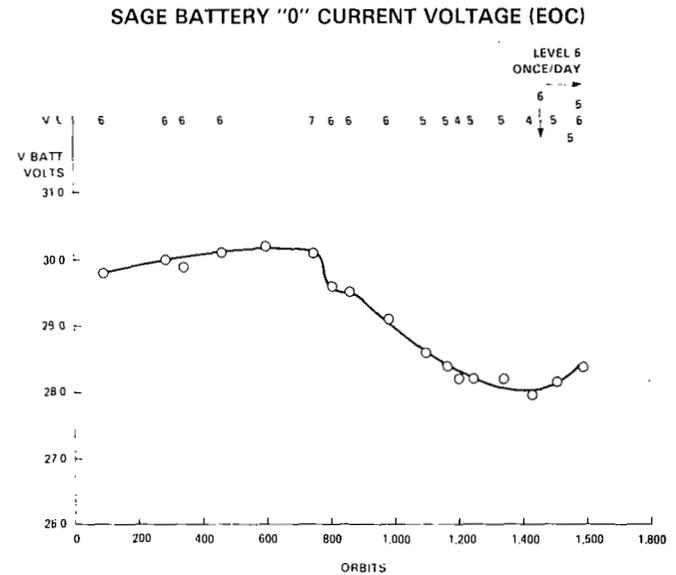


Figure 3-47

NEGATIVE ELECTRODES E/P-SAGE SIDE 1



POSITIVE ELECTRODES E/P-SAGE SIDE 1

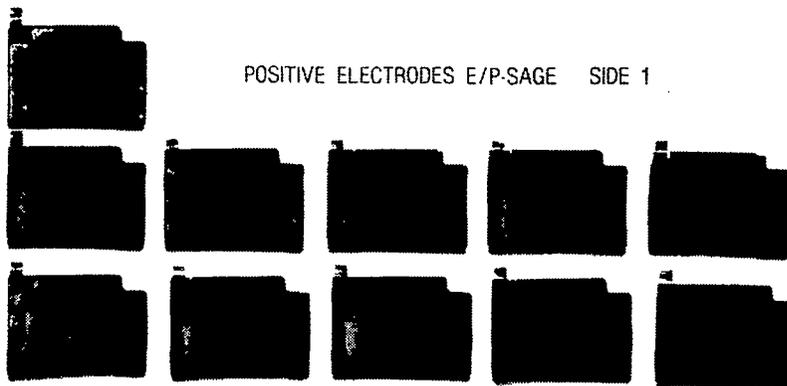


Figure 3-48

ANALYSIS OF NICKEL-CADMIUM CELLS FROM THE HCMM AND SAGE FLIGHT LOTS

	LOT 1 (HCMM)		LOT 2 (SAGE)	
	S/N #214 Uncycled	S/N #256 Life Test (10 K Cycles)	S/N #291 Parametric Test	S/N #318 Uncycled
Pos. Pl. Wt.	8.24 g	8.60 g	8.62 g	8.89 g
Neg. Pl. Wt.	10.60 g	9.76 g	9.83 g	10.29 g
Pos. Thick.	29.10 mils	31.58 mils	28.84 mils	28.27 mils
Neg. Thick.	32.60 mils	33.50 mils	31.16 mils	31.70 mils
Pos. Chem. Cap.	14.30 Ah	15.00 Ah	12.94 Ah	12.12 Ah
Neg. Chem. Cap.	30.37 Ah	26.38 Ah	20.52 Ah	23.26 Ah
Pos. E Chem. Cap.	11.67 Ah	**	13.75 Ah	11.25 Ah
Neg. E Chem. Cap.	16.82 Ah	**	15.60 Ah	18.24 Ah
Electrolyte OH <sup>-</sup>	100.79 meq.	162.11 meq.	101.79 meq.	98.10 meq.
Electrolyte CO <sub>3</sub> <sup>2-</sup>	138.28 meq.	74.18 meq.	108.28 meq.	90.60 meq.
Total meq.	239.07 meq.	236.29 meq.	210.07 meq.	198.70 meq.
Electrolyte as OH <sup>-</sup>	42%	69%	48%	52%
Electrolyte as CO <sub>3</sub> <sup>2-</sup>	58%	31%	52%	48%

\*\* These tests have not yet been performed.

Figure 3-49



## ESA BATTERY DEVELOPMENT

H. J. Young and D. Goudot  
ESA

I should also mention that Dr. Goudot and myself are based at the Nuclear Space Agency's Technology Center at Noordwijk in the Netherlands. ESA's activities for battery R&D are confined to applied programs, that is to say, they must be directly related to future ESA projects.

There is coordination with CNES, the French Space Center in order to harmonize the R&D investment with the sole manufacturer in Europe, namely SAFT. Although having an evident disadvantage, this monopoly, in practice, permits efficient rationalization of development and gives automatic standardization and continuity in the products with consequent increase in relevant experience with them.

The ESA program for some years has been concentrated upon three main objectives.

(Figure 3-50)

First, we are interested in the development of a higher capacity family of nickel-cadmium cells in the range of 25 to 60 ampere-hours.

Secondly, we are trying to improve the existing NiCad range, which extends up to about 26 ampere-hours, the emphasis being on weight reduction and quality. That is to say, we are trying to enhance the mechanical and electrical behavior and lifetime.

Thirdly, our main development is in silver hydrogen cells. In addition, we cooperate with CNES, the French agency, in nickel-hydrogen development.

The first figure also shows the evolution of these developments. Taking the first of these three objectives, the high capacity cells are now being requested for some application satellites, mainly telecommunications, with power demands of up to 2 kilowatts during the eclipse.

In consequence, it is planned to develop a cell of approximately 40 ampere-hours in the 1980 to 1981 timeframe. It is intended to use the same technology as existing SAFT, 4- to 26-ampere hour range, following the current operating modes, limits, and so on.

It is expected to achieve an energy density of around 40 watt hours per kilogram at 100-percent DOD. It is probable that the new family will have a common footprint modifying the height as the simplest means to achieve various capacities.

This approach, which has been satisfactorily adopted for the current standard range, allows for extensions of the size with a minimum of development cost and delay.

The second of these main objectives, the improvement of the existing design, includes, first, the achievement of a better understanding of the cell thermal behavior. Following a study contract with Elektronikcentralen of Denmark, it is now possible for us to undertake realistic thermal predictions at battery level. This will be referred to a little bit later in context of the silver hydrogen cell development.

Next, the saving in weight of approximately 5 percent for the 23-ampere-hour-size cell in the current range has been made possible by reduction of the can wall thickness.

(Figure 3-51)

This is from 0.6 to 0.4 millimeters. It was found, however, that the thinner wall doesn't produce changes in the mechanical behavior of the battery level requiring a different approach to the design of the battery structure.

This figure shows the current ECS battery, which is the European Communication Satellite battery's design, using the recently qualified thin wall cell and showing the lightweight structure adopted. In fact, there were titanium rods and end plates. Next, a new mechanical design for the internal connections of cell electrodes for improvement of the vibration capability has recently been qualified at 22 grms in parameter.

(Figure 3-52)

The design will be incorporated in cells of the next ECS battery model, and it is expected to be adequate to meet the anticipated levels of both the Ariane launcher and the shuttle.

The figure shows the new leaf spring design that has been adapted. More recently, 7-ampere hour cells for the Exosat project, using this design successfully withstood a level of 28.5 Grms. We expect this design to have some reserve as well in this respect.

In fact, with this number, there is an additional nylon locking piece that goes between the top of the cell and the electrostack to push in the stack during vibration.

(Figure 3-53)

A summary of the qualification procedure applied to the ECS cells with details of the vibration spectrum is given in the next vignette. At the 22 Grms level, development SAFT models successfully withstood about 30 minutes endurance in each axis.

Next, a study of electrochemical impregnation of the nickel electrode was completed in 1976, and subsequently a pilot manufacturing unit was built under the sponsorship of CNES. This would have sufficient capacity to meet the future European needs. This anticipates that the advantages of this technique are confirmed by samples currently in cyclic testing.

(Figure 3-54)

This vugraph shows the progress to date comparing the evolution of thickness of electrochemically and chemically impregnated electrodes to date, and the advantages of the electrochemical technique have been well demonstrated. For instance, there are some unimpregnated electrodes shown in the graph. That is the middle curve.

A study of the plastic bonded cathode, which, for the moment, completes our various improvements, is in progress with the intention of further weight reduction of NiCad cells. We hope to introduce this type of electrode in lightweight cells in the near future, and some results should be available by the end of 1980.

The third and largest of ESA's objectives is the successful development of the silver hydrogen cell. This activity started in 1974 with the feasibility study by Batelle predicting the possibility of achieving 80 watt-hours per kilogram and a lifetime of between 4 and 5 years.

(Figure 3-55)

Since that time, following systematic studies of silver electrodes, electrolyte management, and separator materials, the first generation cell was realized. This silver hydrogen cell, developed and shown in the next figure, was reported by SAFT at last year's symposium at Brighton in 1978. The figure shows it compared in size with the current NiCad and nickel-hydrogen cells of approximately a different capacity.

(Figure 3-56)

The development of a second generation hydrogen electrode is now being considered. This was seen previously to be a limiting factor in the performance of the present cell. Concurrently, following the review of all components, a detailed mechanical design study is soon to begin on a spherically shaped cell, and a working prototype of this cell is shown in the next figure. It is at 24 ampere-hours.

The present situation indicates already that better results than those predicted are achievable with an energy density of 90 watt-hours per kilogram and a comparable volumetric efficiency to NiCad cells.

(Figure 3-57)

This figure provides comparative weight breakdown of nickel cadmium, nickel hydrogen, and the two generations of silver hydrogen cells. Just in case any of you noticed, this figure here proved to be somewhat optimistic. This one is somewhat pessimistic.

I think this relates to Inconel 718 contained in that Inconel 65. As you can see here, we are getting 91 watt-hours per kilogram for the spherical cell. If you look at the volumetric efficiency, we are showing a very good capability versus the NiCad.

Prototype cells which have been in test for 2 years have been submitted to 24-hour cycles at 50-percent DOD at both 20 and 0°C. After approximately 550 cycles at 20°C, some problems are evident as shown in the figure.

(Figure 3-58)

The cause was attributed to short circuits caused by dimensional changes of the positive electrodes. The new design will avoid this feature, but up to the point of failure, no other problems were observed.

At 0°C, the test is still running, after 700 cycles without any sign of failure, as shown in the next figure.

(Figure 3-59)

In these figures we must relate the pressures to the overall capacity available. In low-orbit conditions (i.e., with 100-minute cycles), the test has been in progress at 20°C and 25-percent DOD.

(Figure 3-60)

This test is still running after 10,000 cycles. An initial variation in performance, as you can see in this figure, is so far unexplained. However, the cell continues to give very satisfactory performance. I should also explain that these graphs are average data. In fact, the spread in reality was not too great.

(Figure 3-61)

Storage testing first performed on samples in 1977 gives very attractive results, indicating a comparable self-discharge to NiCad cells. This next figure shows a loss of 15 percent after 1 month at 20°C and 8 degrees at zero.

(Figure 3-62)

It should be noted that this attractive behavior of the silver hydrogen couple is derived using components available some 3 years ago.

In 1978, a thermal study of nickel-hydrogen and silver hydrogen cells was carried out by Elektronikcentralen. Following a component analysis, a thermal model was constructed as shown in this next figure, and this rather complex model shows the calculated delta temperatures at specified nodal points of the cell for a constant 1-watt dissipation within the electrode stack.

The results gave good correlation with values measured in practice. The results have also shown, however, that the heat evolution is rather greater than that of the equivalent NiCad cells, and modifications will necessarily be introduced in the second generation cell design to improve heat dissipation and assist in definition of future battery structures.

It is envisaged that an egg-box like structure would be a likely solution to the encapsulation of the spherical shape. As I mentioned previously, a further contract is now planned to study this cell design.

In parallel, looking at possible effects of hydrogen embrittlement and long-term high-pressure cycling, we are conducting a contract at Ecole Centrale in Paris. The smaller volume of the spherical cell will necessitate a working pressure of 50 bars at the end of charge. The question of safety in both design and operation of metal hydrogen batteries has to be considered, and the study of safety aspects is the prime objective of this metallurgical study.

In preparation for the future, a system study contract for metal hydrogen cells will be given to one of the leading European prime contractors within the next few months. This study will analyze the problems of integration into spacecraft, looking at the mechanical, thermal, and electrical interfaces.

However, it should not be concluded that metal hydrogen will automatically replace NiCad in ESA applications. For example, the merits of nickel hydrogen at least appear to be questionable, to us at least, and historically systems with silver electrodes have not demonstrated the best life-times. The choice will necessarily be a question of tradeoffs, case by case.

In the near future, it is intended to concentrate our efforts in the ESA battery test center to the evaluation of both nickel hydrogen and silver hydrogen to define the cell characteristics and to determine operation modes and to assess life duration, with the eventual objective of qualifying cells.

(Figure 3-63)

This series of figures shows the test center at Noordwijk and details of some nickel-hydrogen tests that we are doing for CNES.

(Figure 3-64)

In the center we can test exactly 100 batteries if necessary, 100 different tests. We have 2000 different data channels.

(Figure 3-65)

This test done at CNES is comparing the performance and life cycling of the cells with the standard 23-ampere-hour nickel-cadmium space cell.

(Figure 3-66)

This is a closeup, a detail of the cells being tested showing pressure transducers at the top.

I have very briefly described our program which is rather ambitious technically, but is limited inevitably by budget problems—in fact, in order to achieve our project readiness, we spend something annually like \$300,000.

Finally, this last figure provides a table with details of batteries used with ESA spacecraft.

(Figure 3-67)

It is a record that appears to be comparatively good up to the present time, and we hope it will remain so. I think I can give you a few minutes to look at that. But, of course, we used the first European battery on ESRO IV, the SAFT cylindrical cell. I think I should point out it is in this HEOS 1 we have got an orbital life of over 7 years. This doesn't apply to the silver cadmium battery.

In the Meteosat 1, we have been experiencing a capacity degradation of almost 50 percent, which we attribute to bad battery manufacturing. We have a solution to restore this to full capacity in the next few weeks.

I think I will finish there. I would like to acknowledge the assistance of SAFT, who provided a lot of the data.

## DISCUSSION

RITTERMAN: You pointed out some electrochemically impregnated positive data, and you showed, I think, that there was hardly any swelling or no swelling of that electrode.

Could you comment on the loading level and the nature of the electrochemical impregnation? What solution is it impregnated from, and how many grams per cc void of active materials did you have impregnated?

GOUDOT: We have no data on that question. Even SAFT has no data. But that can be provided.

GROSS: You indicated on one of your charts that for the OTS spacecraft, you had a new battery management technique. Could you discuss what it was and why it was necessary, and what it did?

GOUDOT: It's a new technique we are applying in OTS. It was based on tests we performed in the laboratory. It was based on the fact that we have a minimum of overcharge in the battery, even to keep the state of charge lower than 1. We observe, in fact, in low orbit with a test performed at 80-percent DOD at 20°C, three times expansion of the lifetime you have normally with the commercial technique.

The technique used in OTS was to let the battery choosing the recharge capacity by recharging with a low-recharge coefficient; 1.2 in the beginning, until the battery reached the lower

voltage in the charge, percent voltage, and at this moment the K factor was increasing by 3 percent, and each time by 3 percent. For the time being, after 2 years mission the coefficient is 1.05 awaiting the degrading of voltage conditions until there is volting with present forms. And this technique normally must double the lifetime, at least.

GROSS: There was laboratory data to base that operation on?

GOUDOT: Yes. We have that available for low orbit as well as geosynchronous orbit. Many years.

GROSS: Second point. It was indicated on the chart that the ISEE spacecraft had a battery failure. Could you discuss what that was?

GOUDOT: In this project, due to the change of load during this period, it was not possible to do the same technique as OTS, requesting very stable loading. There we come back to the common scenario technique having voltage limitation at the end of charge. As I remember, it is a 16-step voltage for end of charge as well as limitation. It is more common for that scene.

YOUNG: About all I can say is that the limiting factor is the current carrying capability paper, but in the second we were operating at 1.02K factor. That is the ratio of charge-discharge. It's currently at 1.05 after 4 eclipse periods.

I think your second question was, if I understood, you were asking what the failure was on ISEE? In fact, this was shorting in cells, so the battery is now disconnected in the spacecraft.

DYER: Can you comment further on the limitations of your hydrogen electrode design, the original hydrogen electrode design? You mentioned you have a second generation hydrogen electrode.

YOUNG: About all I can say is that the limiting factor is the current carrying capability of the hydrogen electrode. The next design will be a lighter weight construction, but it will also have a much greater current carrying capacity. I can't remember offhand what the density is for that electrode.

GOUDOT: We are going to develop a new hydrogen electrode, because we developed silver electrode and its performance is now so good, we are limited by the hydrogen electrode. Following that we are forced to develop a new type of electrode because what we used until now was coming from the fuel cells development more than 10 years ago.

YOUNG: As an additional comment on that, we use a thick electrode in the silver hydrogen cell anyway, which means that we are using fewer hydrogen electrodes in the silver hydrogen cell. So it has to be beefed up a little.

VAN OMMERING: I would like to mention that the data shown on the nickel-electrode expansion were actually developed with the Intelsat contract with SAFT. The loading levels that

were involved there were about standard loading level for the chemically impregnated electrodes. And under-impregnated electrodes were about 70 percent, which was standard level. The electrochemically impregnated electrodes have the same loading level as was under-impregnated chemically made electrodes.

As a matter of fact, a question, I wonder if you would elaborate on your assessment of nickel-hydrogen technology. It is questionable at this point.

YOUNG: Thank you for the first comment. The opinion we have about the nickel hydrogen is that when you take into account the loss of volumetric efficiency, I think that we can also make the point, the problem with the nickel-cadmium system is related largely to poor battery management on the spacecraft.

I think one should get above all the noise, discussing what we should and shouldn't do. I think one should get a well-managed battery. I don't think the differences in performance are going to be that great. So overall we don't think that the energy density and the watt-hour efficiencies will show significant improvement on the nickel cadmium.

RITTERMAN: Are you confident that the hydrogen electrode was the limiting electrode in silver hydrogen? Could you and the other gentleman comment on the other density where the limitation occurred, or the rate of discharge where the limitation occurred on the hydrogen electrode?

YOUNG: I am personally not competent about that.

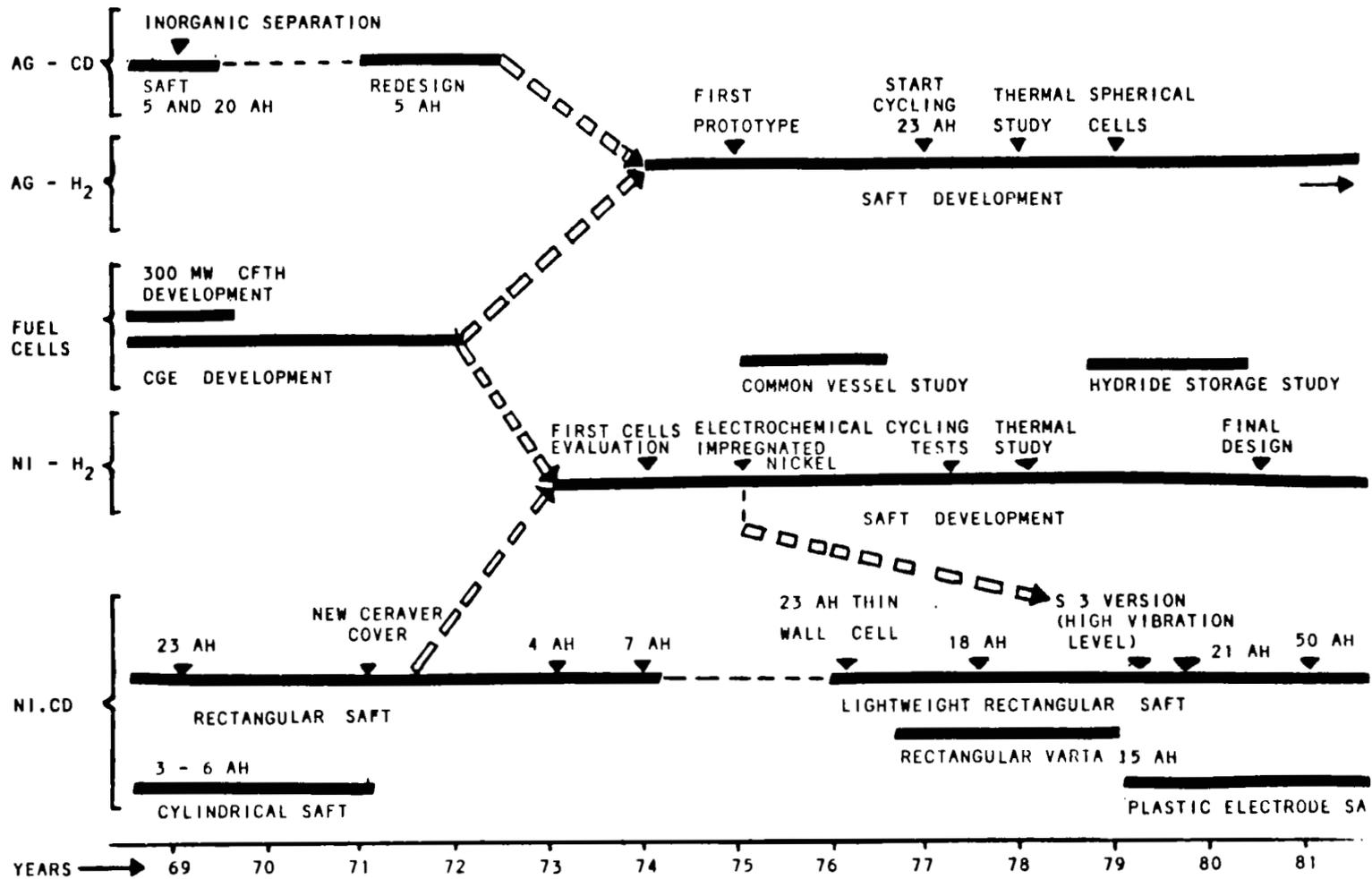
GOUDOT: We have no memory, and we have no data there. But we have a report, and we can provide the data to you if you want.

OTZINGER: Are you getting favorable results from your silver hydrogen work? Can you tell me what the separation system consists of?

YOUNG: Apart from the conventional answer of various polymers, etc., I will ask the SAFT representative to answer that. What the separator constituents are with silver hydrogen.

FOUGERE: The separator constituted from the membrane associated with, number one, nylon; several layers of cellophane type membrane; plus several layers of nylon.

SPACE BATTERY DEVELOPMENT IN EUROPE



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Figure 3-50

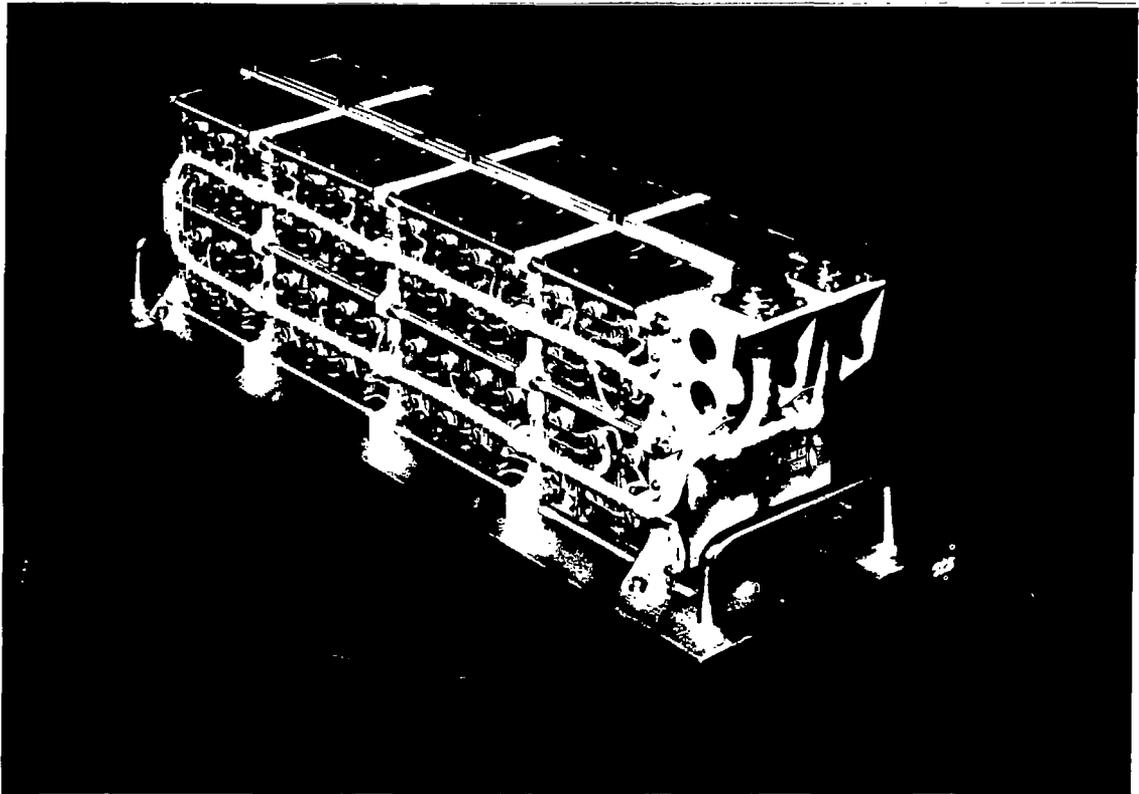


Figure 3-51

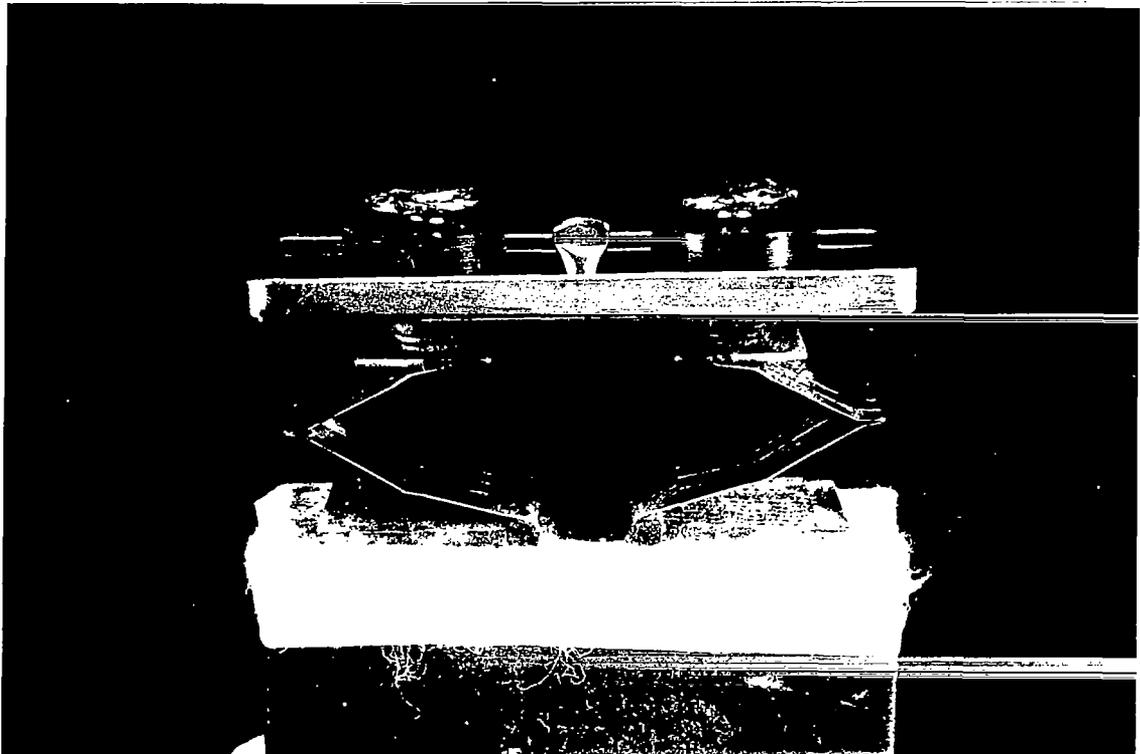


Figure 3-52

SUMMARY PROCEDURE

NI-CD CELL QUALIFICATION SPECIFICATIONS - VO S 3 SERIES

1. VISUAL INSPECTION + LEAK TEST
2. STANDARD CAPACITY
3. LOW TEMPERATURE CAPACITY (-20°C)
4. HIGH TEMPERATURE CAPACITY (30°C)
5. OVERCHARGE
6. CHARGE RETENTION
7. MECHANICAL TESTS ←
8. CHARGE RETENTION
9. INTERNAL RESISTANCE
10. STANDARD CAPACITY
11. LEAK TEST

1. LINEAR ACCELERATION  
± 20 G 1 MIN/AXIS X, Y, Z
2. VIBRATION SIMUSOIDAL (2 OCT/MIN)
 

5 - 15 HZ	11 MM. DISP.
15 - 35 HZ	10 G.
35 - 60 HZ	20 G.
60 - 70 HZ	10 G.
70 - 100 HZ	7 G.
3. VIBRATION RANDOM

UP TO 100 HZ	+ 3 DB/OCT.
100 - 240 HZ	1 G <sup>2</sup> /HZ
240 - 1000 HZ	- 6 DB/OCT.
1000 - 2000 HZ	0.058 G <sup>2</sup> /HZ

NOTE : UNLESS OTHERWISE STATED ALL TESTS ARE AT 20°C.

TOTAL GRMS = 22  
DURATION 5 MIN/AXIS

Figure 3-53

(SAFT INFO)

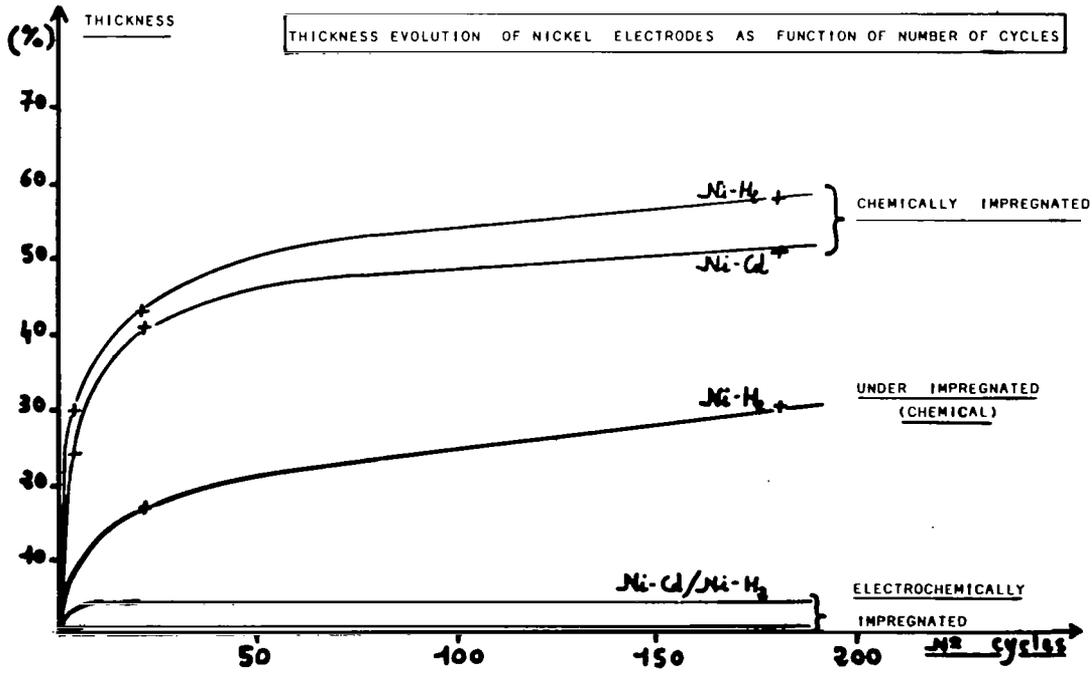


Figure 3-54



Figure 3-55



Figure 3-56

COMPARATIVE WEIGHTS - METAL-HYDROGEN AND NICKEL CADMIUM

	NICKEL HYDROGEN (25 AH)	SILVER HYDROGEN (75 AH)		NICKEL CADMIUM 23 AH (53 TYPE)
		1ST GENERATION	2ND GENERATION	
POSITIVE ELECTRODES	250 (40.2%)	71 (18%)	71 (23.6%)	292 (29.05%)
NEGATIVE ELECTRODES	54 (8.7%)	27 (6.9%)	18 (5.9%)	390 (38.8%)
SEPARATOR	8 (1.2%)	18 (4.6%)	12 (4.0%)	26 (2.6%)
ELECTROLYTE	100 (16.1%)	78 (19.8%)	50 (16.6%)	110 (10.95%)
CONTAINER + TERMINALS	150 (24.1%)	160 (40.6%)	120 (39.9%)	183 (18.2%)
MISCELLANEOUS HARDWARE	60 (9.7%)	40 (10.1%)	30 (10.0%)	4 (0.4%)
TOTAL (GM.)	622	394	301	1005
VOLUME (CM <sup>3</sup> )	635	469	268	336
ENERGY DENSITY (WH/KG)	50	70	91	35
VOLUME EFFICIENCY (MH/CM <sup>3</sup> )	49	59	103	99

Figure 3-57

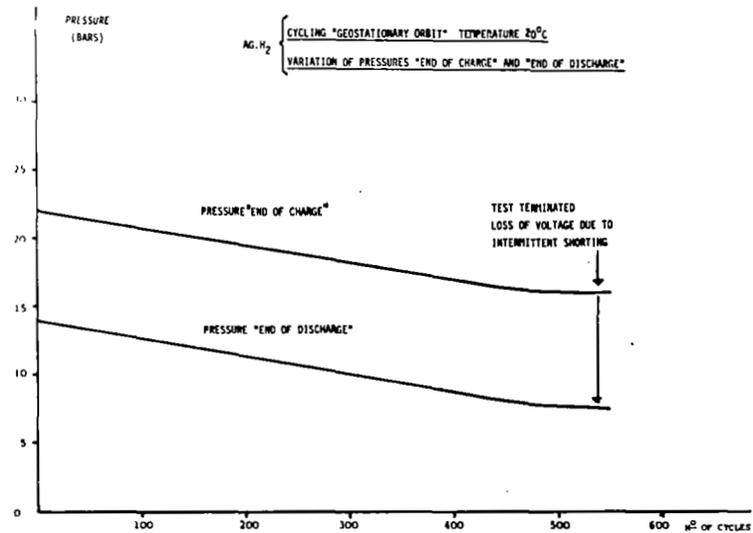


Figure 3-58

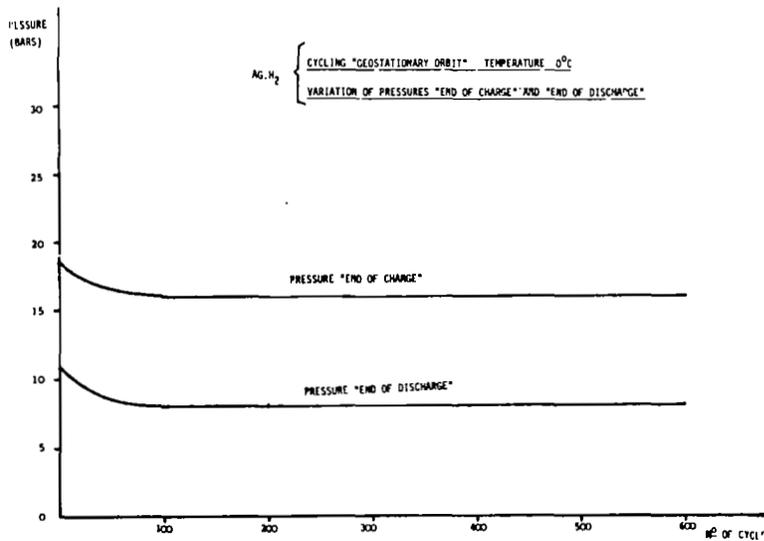


Figure 3-59

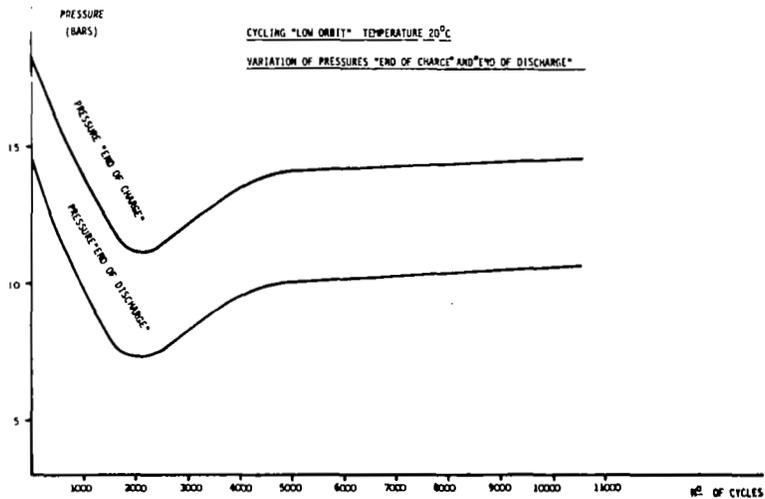


Figure 3-60

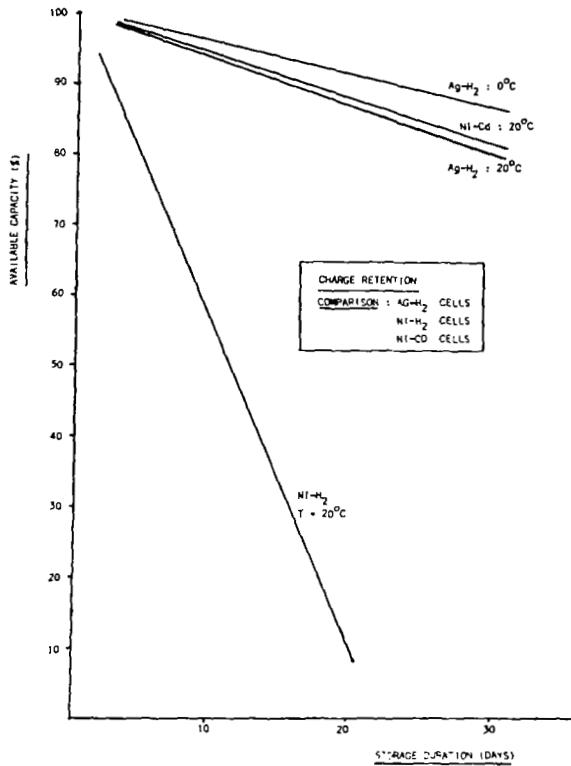
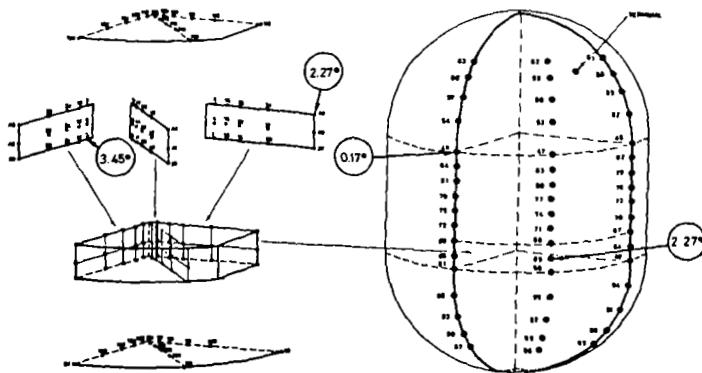


Figure 3-61



AG-H<sub>2</sub> - CELL. TEMPERATURE EXTREMES FOR ONE WATT DISSIPATION. CELL IN CALORIMETER.

Figure 3-62

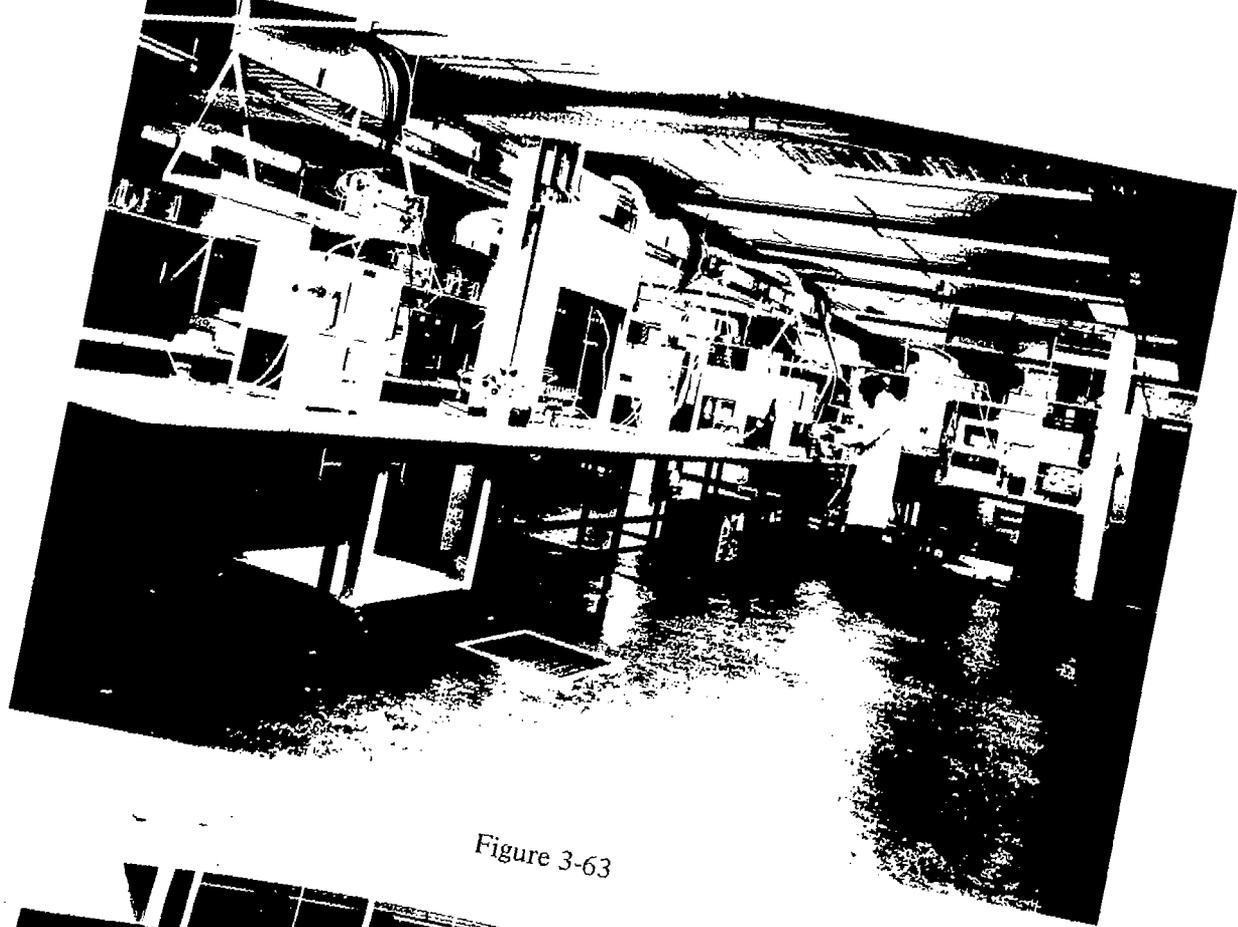


Figure 3-63



Figure 3-64

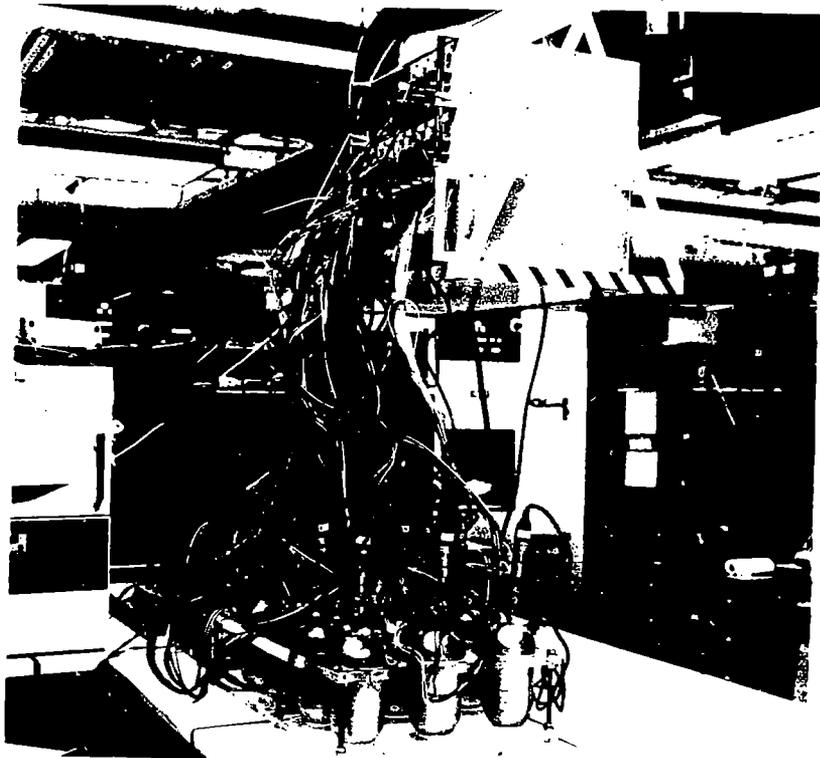


Figure 3-65

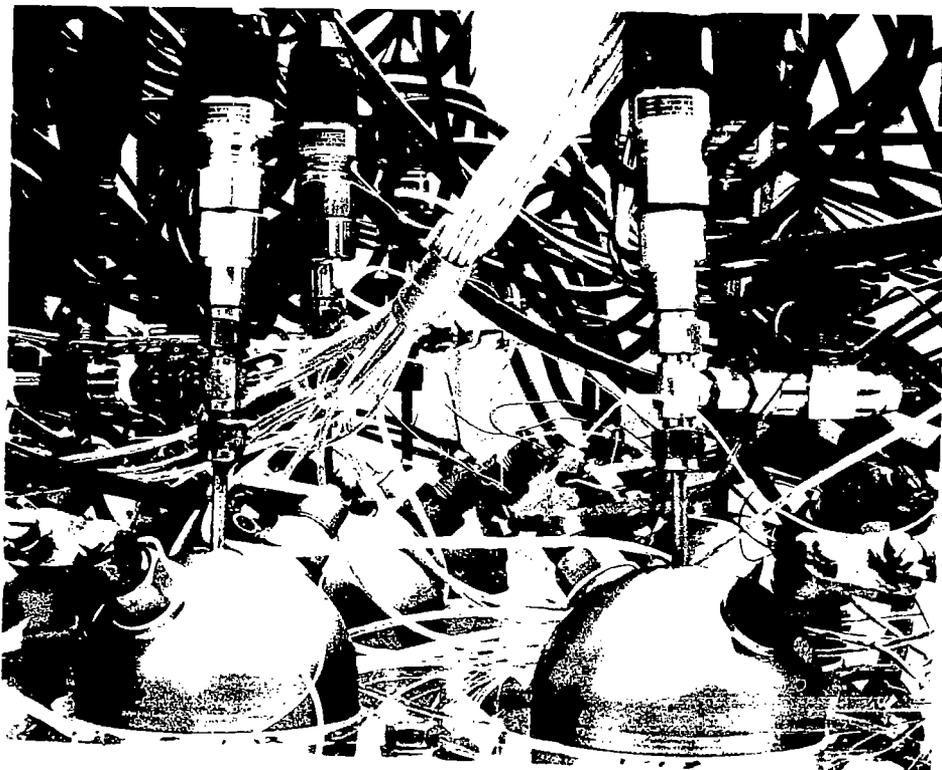


Figure 3-66

BATTERIES USED ON ESA SPACECRAFT

SATELLITE	MISSION	LAUNCH	ORB. LIFE (YRS)	BATTERY TYPE	MANUFACTURE	REMARK
ESRO 11/IIA	COSMIC RAYS	MAY 67/ MAY 68	3	1 x 16 C, 3 AH NI.CD	GULTON	3 YEAR MISSION, NO ANOMALY
ESRO 1A	AURORAL/ IONOSPHERE	OCT 68	2	1 x 16 C, 3 AH NI.CD	GULTON	2 YEAR MISSION, NO ANOMALY
NEOS 1/2	SCIENTIFIC	DEC. 68/ JAN 72	7/2	1 x 19 C, 5AH 1 x 21 C, 5AH AG.CD	YARNEY	2 YEAR MISSION, NO ANOMALY
TD 1	ASTRONOMY	MARCH 72	2	1 x 16 C, 15 AH NI.CD	GULTON	2 YEAR MISSION, NO ANOMALY
ESRO IV	IONOSPHERE	NOV. 72	2	1 x 20 C, 6 AH NI.CD	SAFT	CYLINDRICAL CELLS
COS - B	GAMMA RAYS	AUG. 75	4	1 x 18 C, 6 AH NI.CD	SAFT	CYLINDRICAL CELLS
GEOS 1/11	MAGNETO- SPHERE	APRIL 77/ JULY 78	1+	1 x 14 C, 16 AH AG.CD	YARNEY	NO ANOMALY
OTS 1/11	EXPERIMENTAL COMM.	SEPT. 77/ MAY 78	1	2 x 14 C, 18 AH NI.CD	SAFT	NEW BATTERY MANAGEMENT TECHNIQUE
ISEE - B	MAGNETO- SPHERE	OCT. 77	2	1 x 16 C, 10 AH AG.CD	YARNEY	BATTERY FAILED AFTER PREDICTED 2½ YEARS
METEOSAT 1	METEO. (GEOST.)	NOV. 77	2	1 x 16 C, 7 AH NI.CD	SAFT	SEE NOTE
MARECS A, B, C	MARITIME OPERATIO- NAL	80/81/82	(7)	2 x 28 C, 23 AH NI.CD	SAFT	} NOT YET LAUNCHED
ECS 1/2	COMMUNI- CATION OPERATIO- NAL	81/82	(7)	2 x 28 C, 23 AH NI.CD	SAFT	
METEOSAT 2, 3	METEO. OPERATIO- NAL	80	(5+)	2 x 16 C, 7 AH NI.CD	SAFT	
SIRIO 2	EXPERI- MENTAL	81	(2)	1 x 23 C, 4 AH NI.CD	SAFT	
EXOSAT	GAMMA RAYS	81	(2)	2 x 16 C, 7 AH NI.CD	SAFT	

NOTE : CAPACITY REDUCED FROM 8 to 4.5 AH AFTER 2 YEARS IN ORBIT :  
CAUSE OF DEGRADATION LIES IN BATTERY MANAGEMENT APPROACH  
(RECOVERY POSSIBLE)

Figure 3-67



# PARALLEL 50 AMPERE HOUR NICKEL CADMIUM BATTERY PERFORMANCE IN THE MODULAR POWER SUBSYSTEMS (MPS)

D. Webb  
McDonnell Douglas

Modular power subsystems is one of the major subsystems of the NASA multimission modular spacecraft. Module 2 was subjected to a temperature vacuum test at McDonnell Douglas Astronautics Company in St. Louis in June 1979. Parallel data to follow was generated during that testing.

Before we address that data I would like to discuss a few things briefly: the test objectives and the approach. Secondly, I would like to talk a little bit about the module with respect to the power circuit, the charger operation, and the data system. And third, a few comments on the batteries.

The test objectives were twofold. It was a thermal test, mainly. The first objective was to establish the system thermal performance under controlled conditions. The second objective was to demonstrate the ability of the components and structural parts to tolerate extremes in temperature.

To accomplish the first objective, the module was subjected to worst-case space environment, either a hot or a cold condition, while the components were generating waste heat at design rates, either high rates or low rates, depending on the environmental conditions. After stabilization of the components, the temperatures recorded were compared to the thermal model predictions and were used as acceptance criteria for the model.

The second objective was accomplished by artificially raising or lowering the stable temperatures that were determined in the first part of the test, and then demonstrating adequate and acceptable system performance in near-Earth orbit simulation. These simulations were 36 minutes of discharge and 56 minutes of charge.

The module is a passively cooled system, and as I said, the components were artificially—the temperatures were artificially raised or lowered by means of thermal control panels, which were facing the module radiator systems or surfaces.

(Figure 3-68 and Figure 3-69)

The module has capability of installing up to three standard 20-ampere hour nickel-cadmium batteries, or three 50 NASA batteries. The configuration that was tested, as you see here, contained three 50s. This is a prototype test to demonstrate full-up capability.

On the center screen you see the brief schematic of the power system. The batteries are as you see here, and the power contractor unit, PCU, that contains the contactors and all of the diodes are as you see here. Also, the current sinters are indicated by the blocks.

As you can see here, there are three batteries in parallel off a common bus fed by a single regulator. The regulator is a standard NASA part and is located near the top of the module.

(Figure 3-70)

The regulator has eight selectable voltage levels, and the batteries are charged until their charged voltage reaches a selected voltage level and that voltage level is maintained until the end of the daylight period.

Normally, the charge goes through two modes of operation in a sunlight phase. The first is where the battery voltage is below the voltage limit mode, or voltage limit established by the selected curve.

The charger will cause the power drawn by the system to track the available peak power drawn by the system to track the available peak power of the array that is feeding the system. It does this by a 70-hertz perturbation signal on the array. I am not quite sure of the change in the power conditions to adjust this output voltage to do this.

Once the batteries have reached the voltage limit, as I say, it is maintained until the end of the daylight period. If the bus demand is greater than the available array power, then the batteries can be in a noncontributing mode, or they can be supplementing the array power by contributing to bus demands. So it is a bus-demand system.

(Figure 3-71)

I wanted to show you this because it has an effect on the data that you will see later on the cycles that we were conducting during the hot and cold testing.

When the regulator is in a cold phase, around 5°C, there is an AC component that is on the bus which is due to the 70-hertz perturbation signal that the charger is injecting into the array. The same type of thing occurs in the hot phase, but you will see that the magnitude of the disturbance is greater. When you take instantaneous readings on bus voltages, you can induce more error.

We know that this is amplified because the screw is looking into a solar array simulator which is hot through the solar array. And there is a compatibility problem between the screw and the power regulating unit and the solar array simulator which goes away.

We have run quite an array test where we have used three batteries in series with a series resistor, and the disturbance is diminished. Also, after you pass from the peak power tracking mode into the voltage limit mode, we find about a 4½-kilohertz AC signal on the bus, which is very much affected by the operating temperature of the regulator. That is shown in the lower figure on the vugraph. I mention this again because you will see these effects on the data.

(Figure 3-72)

The data system that we used to accumulate the data on the battery performance was an analog to digital system, and the parameters of interest with respect to the battery performance are shown here. They are normal engineering ranges, and here is the analog range. These signals are conditioned to this type of a range by a signal conditioning unit which you see here on the modules.

Those voltages at those levels are fed to redundant remote interface units which are the devices that digitize the data. We break into the data bus—this normally goes to a central unit which transmits that information to ground and flight. We break into that data bus with a simulation of that central unit.

We recently worked a computer into the setup so that we can freeze the digital data in various slots and change them back to engineering units and give us the amounts during the testing.

Here again I show you the equivalent of a single count change on the digital system. We will also see some of this effect in the data.

With respect to the batteries, they are twenty-two 50-ampere hour nickel-cadmium cells. The manufacturer is GE. These cells are not a NASA standard. However, a manufacturing control document is used to control their manufacturing and has all the detail that was worked into the NASA standards. The only difference is that it has not been formalized as a NASA standard.

Cells are selected for battery assembly based on the charge voltage and the capacity during zero-degree and 24-degree capacity cycles at the vendor. The plates are chemically impregnated.

(Figure 3-73)

I have only included battery one voltage here. It is typical, instantaneous reading. I show all three battery currents to amplify their uniformity. These are five reading averages. Because of the data problem that we were having, we worked into the program an averaging of five readings to try and smooth the perturbations that we have.

There is only one point on the graph that is not an average, and it will be these points here. Normally, the data is on 4-minute intervals. During the first 120 seconds of charge, we took 10-second data. This is an instantaneous reading here during that 120 seconds. It is a maximum reading.

Once again, this was conducted at voltage level 4. It was a light bus load, 250 watts. The batteries were running about minus 5 degrees. Batteries 1 and 2 were equal as far as temperature is concerned in this test, and battery 3 was running slightly higher by 2 or 3 degrees.

On that instantaneous data taken on the charge, the maximum difference between the batteries on charge was 1.2 amperes. That covered the spread of all three batteries during initial shots. And toward the end, there is 0.72 to 0.76 at the end of the paper.

(Figure 3-74)

I didn't point out on the other one, but you could see the bit change in the bus voltage there. Here you can see a much wider spread in the instantaneous voltages and for the reasons I stated earlier. These are three consecutive cycles in both cases that I am showing.

Seventy-two hours of this type of operation went on at each condition, when the conditions were cold and the batteries were on minimal load, and when the conditions were hot and the batteries were running at 25 degrees and 1200 watts.

Even with the averaging—this is all average—and some of this data going on, the current does follow the instantaneous voltage and we don't get a very smooth curve. In this case batteries 1 and 3 were running equal temperature, and battery 2 was cooler by 2 or 3 degrees. Charge level 5 was used here. I picked level 4 for the cold and level 5 for a reason that will become apparent shortly.

(Figure 3-75)

This shows a variation in top of cell temperature for the three batteries during the cycles that I presented during the hot phase.

You see that we get a heating during discharge and a cooling and indication of a slight heating there at the end of charge on the cycles. It looks as if I picked a couple of cycles here where they may have been fooling around with the TCP's and then dropping off.

Here you see the difference between the batteries in the period that ran cooler. Battery 2 ran cooler, as it says, and battery 1 and 3 were running at very similar temperatures.

(Figure 3-76)

This is a summation of percent factors that we obtained at various levels. As you can see, level 5 and 6 were evaluated during the initial test. The 17 percent that you see here and the 3.6 were data taken from June. Since that time, we have changed some of the components in the module to free them up for use on module number 1, put in new equipment, and we have gone through a current data retest.

The normal configuration of the model when delivered is with two batteries. So what you see is the absence of the third battery. We went through the same levels, same bus wattage levels, in this test that we went through in the first test. Subsequently, the percent depth is greater on the two batteries.

As you saw, the charge current both during the hot test there and during the cold test was somewhere between 14 and 16 amperes maximum. During the second test, the batteries were running somewhere between 21 and 23 amperes maximum during the peak power tracking mode.

Level 7 was analyzed here on one cycle. There were only two cycles with level 6. These are not the total number of cycles around, but the total number of cycles I have down on this.

The conclusion that we draw here is that the parallel battery operation off the single bus with the single regulator feeding it, the performance was certainly consistent and showed no tendency to deviate from that acceptable performance. And we are pleased at the way things went.

## DISCUSSION

THIERFELDER: Is there a current limit on melting point?

WEBB: No, there is no limit. It is the available current.

THIERFELDER: If one battery would short or it went out or was turned off, all the current would not vent to the other two batteries?

WEBB: Yes. I believe there is a paper to follow here shortly on parallel power testing that Goddard is doing under various conditions of shorted cells, or what have you. Jerry, is that limited to imminent current, available current?

HALPERT: 98 amperes, I think.

WEBB: I understand what you are saying. The regulator had six modules in it, or 18-ampere limit on each of those modules. So the maximum current that it can put out is 108 amperes. So what is taken by the bus load, the remainder is for the battery, and it will divide as conditions exist.

YOUNG: Can you tell, were these old or new batteries? How many cycles did you actually do during the test?

WEBB: These were new batteries that were built specifically for testing the module. They had gone through probably 200 to 300 hours of performance testing on the module before we got to this stage. Then we went through a retest here again. So I would say 200 or 300 hours of operation, and probably in the module—we don't keep any track of cycles, so it's probably a good 15 fairly deep depth-of-discharge cycles.

Normally, it is operation of other equipment while the battery is off feeding. So it isn't a purposeful attempt to break them down.

OTZINGER: The body of the battery gets charged directly during the solar array, not directly from the modules? They get charged from the modules?

WEBB: Yes. The batteries directly across the bus, downstream of the screw.

Here you see the unregulated bus. The batteries are directly off that. We have a load bus. Off this comes the module loads, and then there is a contractor that goes to an instrument bus, which feeds the instrument packet.

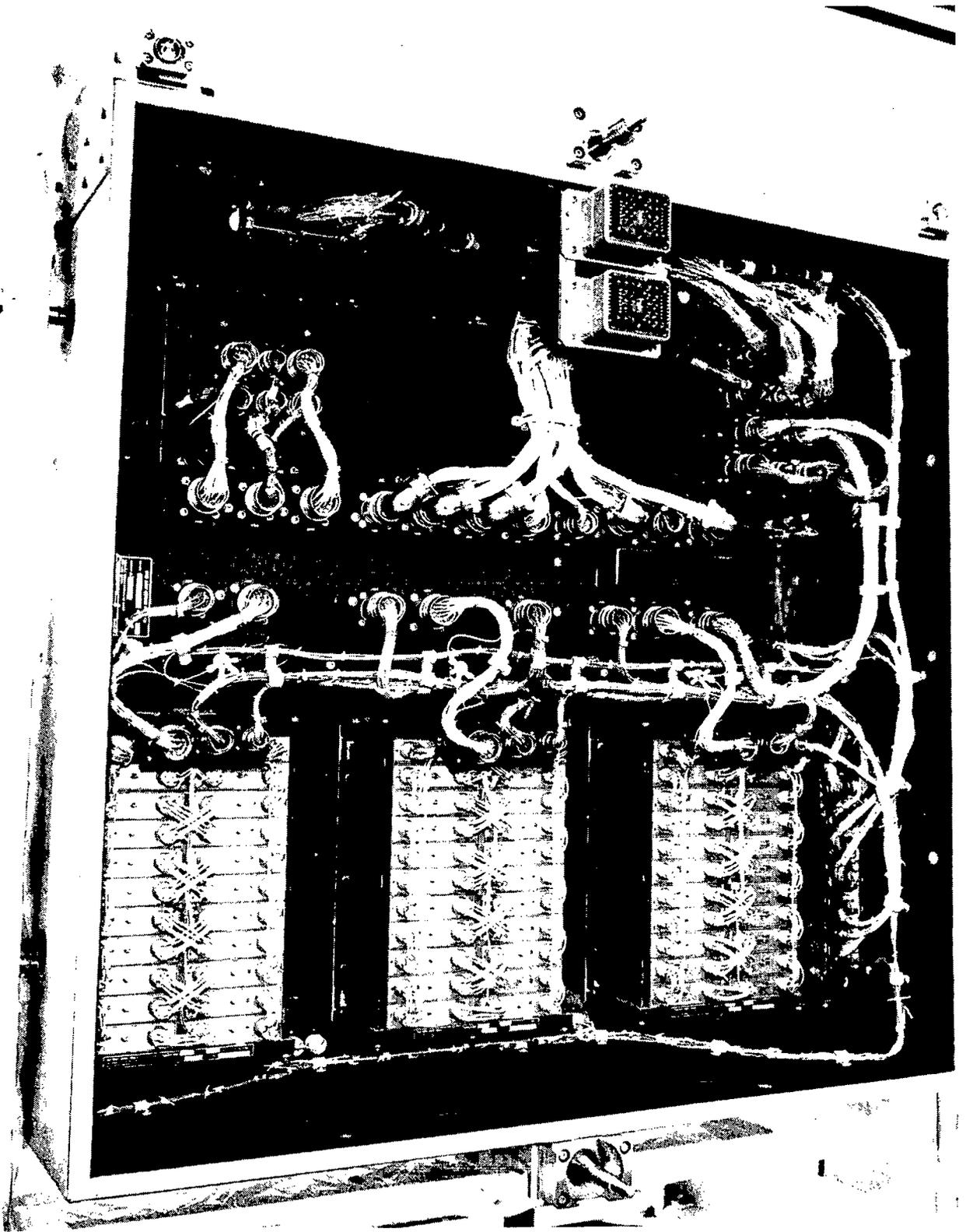


Figure 3-68

POWER CIRCUIT  
MODULAR POWER SUBSYSTEM

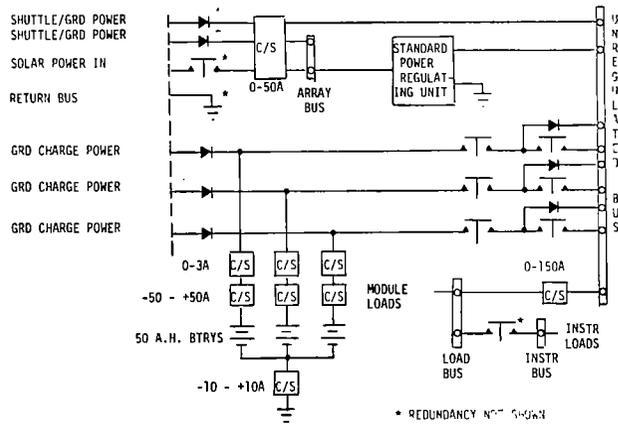


Figure 3-69

BUS EFFECTS VS. REGULATOR OPERATING MODES

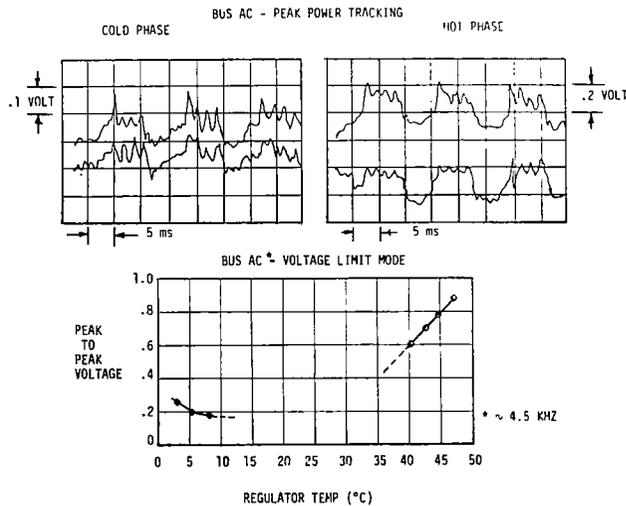


Figure 3-71

SELECTABLE BATTERY CHARGE VOLTAGE LEVELS

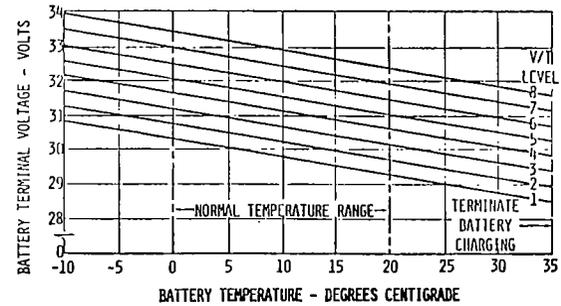


Figure 3-70

MODULE BATTERY DATA SYSTEM - SUMMARY

PARAMETER	FLIGHT MONITOR	RANGE ENGR UNITS	ANALOG OUTPUT RANGE	ACCURACY	TM * RANGE	SINGLE COUNT ENGR EQUIVALENT
BTRY LO I	CURRENT SENSOR	0-3A	0-5V	1% FS**	0-250	.012 AMPS
BTRY HI I	CURRENT SENSOR	-50 TO +50A	0-5V	1% FS	0-250	.400 AMPS
BTRY VOLTAGE	VOLTAGE DIVIDER CIRCUIT	0-40V	0-5V	1/2% FS	0-250	.160 VOLTS
BTRY TEMP	PASSIVE THERMISTOR	+65° - -25°C	.429 - 4.345V	NEGLIGIBLE	21-217	.3°C IN LINEAR RANGE***
HALF BTRY VOLT COMPARISON	VOLTAGE COMPARATOR	-.7 TO +.7V	0-5V	1% FS	0-250	5 MV

\* RIU F/S = 5.12V = 256 COUNT  
\*\* IN TOP 90% OF RANGE  
\*\*\* LINEAR RANGE +40° TO -10°C

Figure 3-72

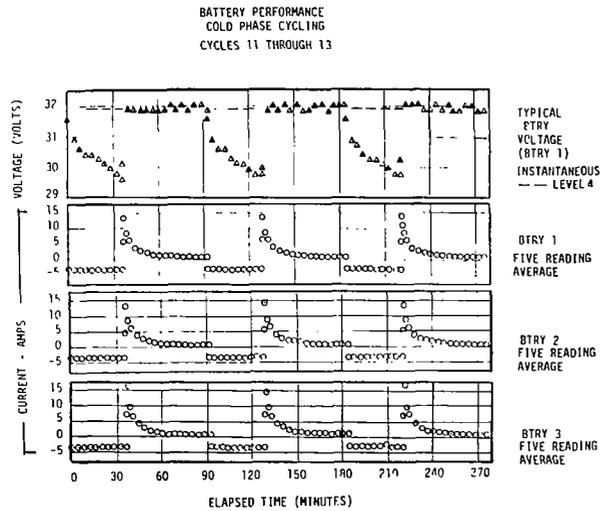


Figure 3-73

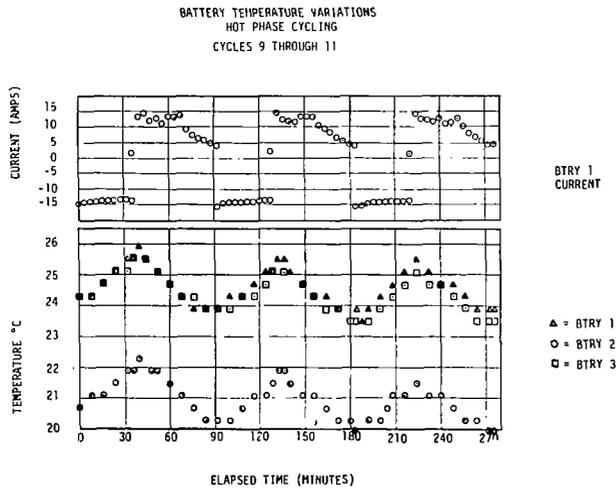


Figure 3-75

BATTERY PERFORMANCE  
HOT PHASE CYCLING  
CYCLES 9 THROUGH 11

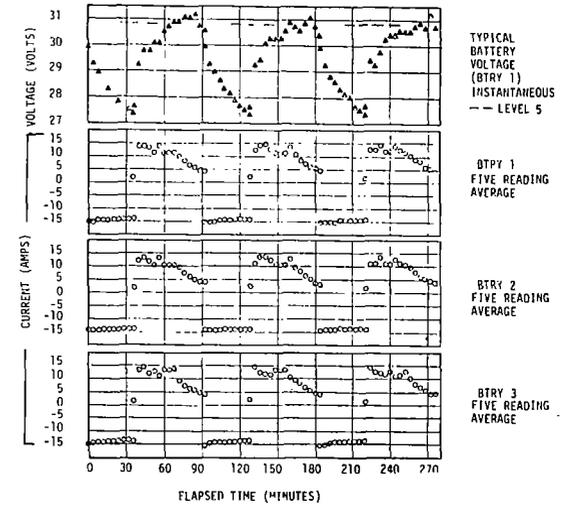


Figure 3-74

CHARGE TO DISCHARGE RATIO RESULTS

PHASE	CYCLE DEPTH	BATTERY TEMPS END OF CHG		VOLTAGE LEVEL	C/D RATIOS*		
		LD	HI		BTRY 1	BTRY 2	BTRY 3
HOT	17% (8.5 AH)	20°C	24°C	5	1.096	1.071	1.128 (10)
	17% (8.5 AH)	23°C	27°C	6	1.258	1.243	1.276 (2)
	27% (13.5 AH)	19.5°C	22.7°C	5	1.026	1.015	— (7)
COLD	3.6% (1.8 AH)	-5.2°C	-2.5°C	5	1.210	1.203	1.313 (7)
	3.6% (1.8 AH)	-5.9°C	-4.9°C	4	1.052	1.047	1.116 (9)
	3.6% (1.8 AH)	-7.9°C	-6.9°C	3	.946	.938	.986 (4)
	5.6% (2.8 AH)	-2.9°C	-1.5°C	5	1.162	1.170	— (10)

\* AVERAGE VALUES OVER THE NUMBER OF CYCLES SHOWN ENCIRCLED.

Figure 3-76

## NASA 50 AMP HOUR NICKEL CADMIUM BATTERY WASTE HEAT DETERMINATION

V. Mueller  
McDonnell Douglas

The test that we ran on the qualification test sample was to determine the waste heat generated in the battery as a function of the discharge rate. The technique involved is essentially calibration of the battery as a heat transfer rate calorimeter. We think the test procedure is rather simple, and it gives consistent results.

(Figure 3-77)

As I said, the objective of the test was to determine the waste heat generated as a function of discharge rate. What we do, essentially, is that we mount the battery on a cold plate, which has a circulating fluid through it and which is temperature controlled, sufficient to maintain a constant temperature at the planned levels of battery activities.

We ran the tests at three different levels of battery activity, one at 40 watts of waste heat generated, one at 60, and one at 100. We start the test by overcharging at some fixed rate, 46- to 100-watt level. We fill the top and bottom. Cell temperatures are stable and remain within  $1/10^{\circ}\text{C}$  over at least a 1-hour period.

By that time, we go directly into a discharge. Our objective is to maintain the same temperature differentials and temperature at each location in the battery. In some cases, we did a very good job of this. In others, we had a little bit of a problem trying to get that waste heat rate adjusted properly.

After we have got that point in general, we continued discharge for at least 2 hours, we discharge and repeat for the next level.

(Figure 3-78)

This is an exploded view of our 50-ampere hour battery, and I show it simply to indicate how it was instrumented.

We have instrumentation on the thermal fins. See the thermal fins interspersed between rows of cells. There are 22 cells, 11 rows, and 10 thermal fins. We have instrumentation on fin 1, which is the first one on the end with the connectors, fin number 6 and fin number 10. The fin that we used to determine top and bottom of cell level was fin number 6.

(Figure 3-79)

This shows how the thermocouples are placed on the thermal fins, 1, 6 and 10. Fine number 6 has the greatest number of thermocouples, and thermocouple number 2 at the top is what we refer to in later charts as top of cell temperature. Thermocouple number 10 is the bottom of cell temperature, and, of course, thermocouple number 10 is directly on the heat transfer surface.

(Figure 3-80)

What I have done here is plotted up some of the data that we got from our 40-watt case, the first case we ran. On the left of this chart we show the overcharge phase, where we are overcharging at 40 watts.

There is the bottom of cell temperature, top of cell temperature. We have a delta of 2°C. As you can see, the variation is fairly minor. The data I plotted here is just at 10-minute intervals, and I just use straight lines to connect them. So you do see some jogging around.

At this point, 70 minutes on this chart, we went from charge to discharge, and we initially set the power level hopefully to maintain the same temperature differential and the same temperature. As you can see, we were a little low at first, and the battery started to cool. When the operator saw it starting to cool, he started cranking up on the current.

We do the discharge at constant current. He finally got the temperature to stabilize, but he overcompensated, and now it started to heat. Again, he compensated for the fact that it was heating and tried to maintain that level temperature of about 20.5°C here. The average power over this time interval was 284 watts.

(Figure 3-81)

We do the same kind of tests for each of the three activity levels that we tested, and this chart plots them as values of delta T versus overcharge and discharge rates. You can see on overcharge it is fairly linear. The three points that we ran are noted on the chart: 40, 60, and 100 watts, roughly.

However, on discharge we did see some curvature. We think that curvature is due to  $I^2 R$  heating, which gives a little bit greater losses at the higher level in terms of percentages, and also the battery temperature, top of cell temperature for that last run, was roughly 2.5 to 3° C, hotter than the previous ones. The previous ones run at 20° C. The last one at about 23.6° C.

I might point out that those percentage levels, 14, 15 percent, etc. are just the ratio of the overcharge rate, the waste heat rate to the discharge rate.

(Figure 3-82)

Our conclusions from the test are that the battery inefficiencies range from 14 to 18 percent at those discharge levels and top of cell temperatures at roughly 20°C. As I noted before, we feel that the test is simple to implement, and it gives consistent results, much easier than a calorimeter would be, for example.

## DISCUSSION

THIERFELDER: Were these done in vacuum or in air?

MUELLER: In air.

THIERFELDER: Were they well insulated?

MUELLER: They were in a pilot box, and they had 3 to 4 inches of styrofoam all around the sides and on top. And the base was mounted on a cold plate.

HENDEE: Were you able to run any stabilized tests throughout, say, the discharge cycle? You must have noticed your percents changing as a function of the state of charge or state of discharge.

MUELLER: On the second test we ran at 60 watts of waste heat. I don't know why we were so fortunate, but we happened to pick the waste-heat rate or the discharge rate exactly. It wasn't necessary to change it throughout the entire distance. We did see a constant discharge during that 60-watt test.

HENDEE: How deep depth of discharge?

MUELLER: I think on the 60-watt case we discharged for roughly 2 hours, and probably I would say was 75- 85-percent DOD. We don't see instantaneous – there's no way to determine instantaneous heat generation here.

PALANDATI: I have two questions. What was the maximum discharge currents that you performed the tests on?

MUELLER: I believe it was between 15 and 20 amperes.

WEBB: On the third test it was close to 23 amperes.

PALANDATI: Basically then  $C/2$ ?

MUELLER: About 23 amperes, right.

WEBB: May I please add: We did on the third run, since we were allowing ourselves 2 hours of discharge during the determination – and at that rate we did run into a condition at the end of the third run where we were depleting capacity and efficiency changed there. I believe John took data from an earlier plateau where heat was stable on that one. But at the end of the test, it did show an increase.

PALANDATI: I have one other question. On your temperatures now, did you always obtain the highest temperature up at the top of the cell, or did you see variations?

MUELLER: No. the highest temperature was measured on top of the cell, yes.

SCOTT: Did you find at a constant current that the efficiency or percent dissipation was a constant? Or, could you tell whether it might be changing with the depth of discharge?

MUELLER: I don't really think that we determined that. What we did was that we established a discharge rate and our objective was to try and hold that discharge rate for roughly 2 hours while we maintained the delta temperatures between the top and bottom of cell constant and the temperatures constant. But instantaneously I don't really know whether the dissipation changed.

SCOTT: If you continued to test for that long at the high end of your discharge rate, you covered a significant change in depth of discharge from the beginning to the end.

MUELLER: Yes.

SCOTT: And you didn't see any difference from – during that time and the percentage dissipation?

MUELLER: No. The only real measure of that one we had was the temperature instrumentation. We did not see that the temperature was significantly changing.

SCOTT: I think the theory would predict that you should get an increase in dissipation as the discharge proceeds from one depth of discharge to another.

MUELLER: I don't know how to comment to that.

WEBB: May I? On the second test, Dr. Scott, the rate that we selected was maintained constant throughout the time that we were looking at the delta T's in the batteries. This was over a good 2-hour period. So that the rate or the DOD on the battery was changing over that period.

We adjusted the wattage continually to keep it at the level, and we set the criteria initially at 0.2 degree change in 1/2-hour period.

MUELLER: One-hour period.

WEBB: One-hour period. Things were going so well that the thermodynamics changed the criteria to 0.1 of a degree change in the hour, and we did not detect a change of that magnitude over the 2-hour period, even though the depth of discharge was continually increasing on that second run. It was very stable.

HENDEE: In my mission simulator, I do it slightly differently. It's a computer-controlled one. I know that the efficiencies change, the more deeply you go into discharge. So if you would look further, you could see. I agree with Scott of TRW that you could see this if you looked a little closer.

MUELLER: I would expect some change as Dr. Scott says, as the discharge continues. Of course, the voltage is decreasing, the current is increasing, and certainly  $I^2 R$  would be increasing significantly. So I don't know that they were a large percentage of the total. I don't think that they were.

WASTE HEAT DETERMINATION

OBJECTIVE:

- o DETERMINE WASTE HEAT GENERATED AS A FUNCTION OF DISCHARGE RATE

PROCEDURE:

- o MOUNT BATTERY ON COLDPLATE WITH SUFFICIENT COOLING CAPACITY TO MAINTAIN CONSTANT TEMPERATURE AT PLANNED LEVEL OF BATTERY ACTIVITY
- o OVERCHARGE AT FIXED RATE UNTIL TOP AND BOTTOM OF CELL TEMPERATURES REACH STABILITY (GOAL  $\leq 0.1^\circ\text{C}$  CHANGE/HOUR)
- o DISCHARGE THE BATTERY AT A RATE TO MAINTAIN STABLE TEMPERATURE CONDITION ABOVE
- o RECHARGE AND REPEAT FOR NEXT TEST CONDITION

Figure 3-77

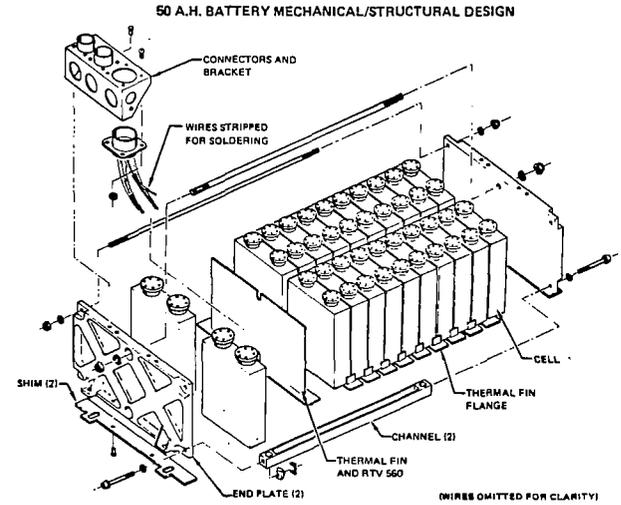


Figure 3-78

WASTE HEAT DETERMINATION  
LOCATION OF THERMOCOUPLES

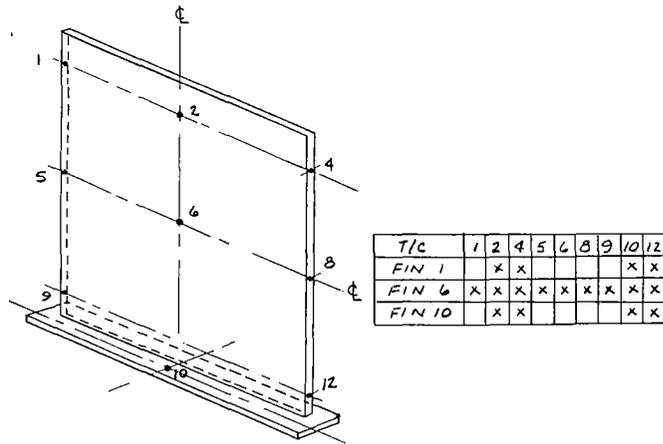


Figure 3-79

WASTE HEAT DETERMINATION  
TYPICAL PARAMETER VALUES

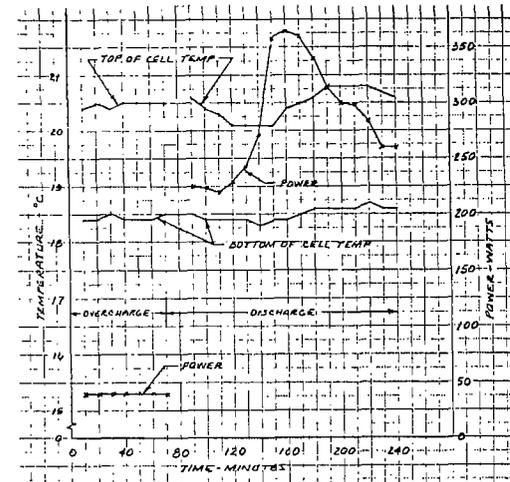


Figure 3-80

WASTE HEAT DETERMINATION  
 BATTERY TOP-TO-BOTTOM  $\Delta$ TEMPERATURES VS POWER RATES

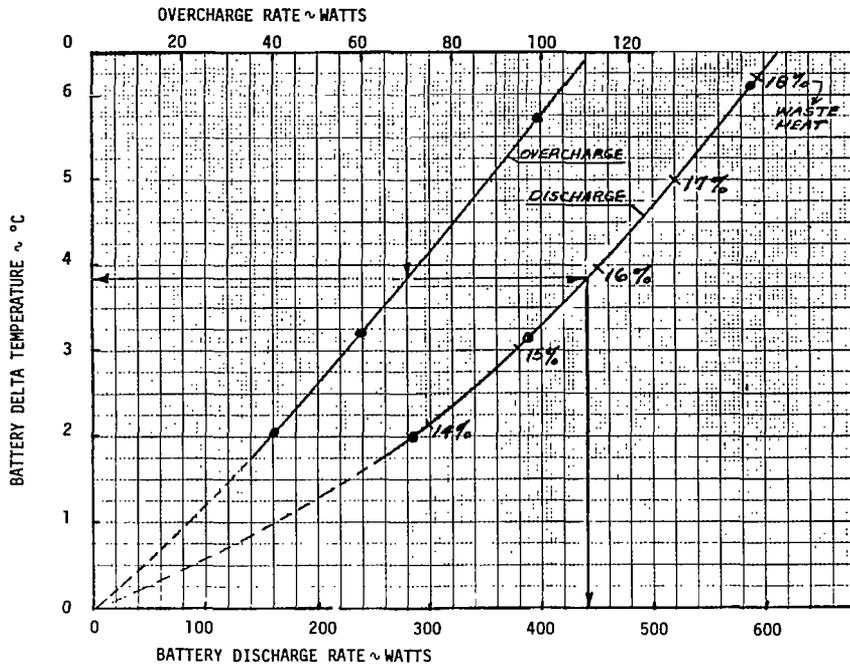


Figure 3-81

CONCLUSIONS - WASTE HEAT DETERMINATION

- o BATTERY INEFFICIENCY RANGES FROM 14 TO 18 PERCENT AT DISCHARGE RATES OF 284 TO 588 WATTS, RESPECTIVELY AND TOP-OF-CELL TEMPERATURES OF 20°C APPROXIMATELY
- o TEST PROCEDURES ARE SIMPLE TO APPLY AND GIVE CONSISTENT RESULTS

Figure 3-82



## THE LDEF HEAT PIPE EXPERIMENT POWER SYSTEM

S. Tiller  
NASA/GSFC

(Figure 3-83)

Future space shuttles are used for transporting a long duration exposure facility, LDEF spacecraft, to and from the near-Earth gravity orbit. The spacecraft was designed to house mobile experiments for long-time exposure duration to space and later retrieval by one of the space shuttles. After retrieval, each unit will be returned to the experimenter for test and evaluation.

One of the experiments that will go on the LDEF is a low-temperature heat pipe experiment designated HEPPS. For the HEPPS experiment, we have designed and fabricated a power system that is located on the top surface of the spacecraft directly above the heat pipe experiment on the side. The location was determined because the power system has solar panels on it, and the heat pipe requires at times to seek cold space.

(Figure 3-84)

This is a functional diagram of the HEPPS pipe experiment power system. The triangle to the left represents four solar array panels. They are miniature panels. The next unit over represents a 12-ampere hour, 18-cell nickel-cadmium battery. And the remaining components within the system comprise an electronic controller.

I would like to point out some of the features of the controller and the battery. Since the spacecraft will be carried by the shuttle in the forward compartment, we have designed some safety features that I would like to point out.

The main bus of the battery is fused to prevent catastrophic failure in case of a dead short on the main bus. During launch and retrieval, the LF spacecraft will enable the load relay only after the spacecraft is placed out in orbit away from the space shuttle. The battery will be launched in the discharge condition. After launch, when we acquire the Sun, the battery will start into a charge phase.

The load relay to the HEPPS experiment will remain open until one of two electrodes indicates that the battery is approximately 100 percent charged and turns on the relay to the HEPPS experiment. If the battery is in a cold condition of minus 10 degrees or less, we have a redundant turnon system that works through the shunt dump regulator.

If the battery voltage reaches 27 volts and the shunt dump circuit starts dumping approximately 100 milliamperes, this circuit can also turn on the relay to the HEPPS experiment.

If at any time the battery voltage drops below 18 volts, or a 0.5-volt delta that is exactly between the two halves of the battery, this would automatically turn it off. The battery will stay, or the relay will stay, in the off-condition until the cycle is again repeated and is turned on again by one of the third electrodes or the shunt dump circuit.

When the shunt dump circuit is active in the cold condition, we use the excess heat and transfer it back to the battery through resistors mounted at the baseplate of the battery.

(Figure 3-85)

Here we see the relative state of charge in the battery during two test cycles of the HEPPS experiment. This is calculated under worst-case conditions during the testing of the HEPPS experiment through two data cycles. After the completion of the second data cycle, the system automatically is clocked off for approximately 10 days to allow time for battery recharging.

(Figure 3-86)

Availability of battery charge current during orbit life is determined by calculating effect of solar array output versus the pseudo angle using data derived from tests of the four solar panels at a one-sun angle.

The data was plotted relative to the two extreme beta angles that they expect the spacecraft to acquire. It was also plotted to a battery voltage of 27 volts. The voltage that the shunt dump regulator will cut off at is approximately 25 volts and gives us an indication of the available power.

(Figure 3-87)

Again, using worst-case conditions, we plotted the predicted battery temperature versus orbit time, using computer calculations from the calculations of the thermal model. However, we expect the battery temperature to be somewhat less than the range that we have predicted here.

I believe the expected range is about plus 35 degrees down to minus 17 degrees. These curves show the battery voltage characteristics during capacity tests conducted at the extreme temperature range of minus 30 to plus 35 degrees.

Now, the capacity curves aren't true overcharge capacity curves. They are the capacity curves that we expect to see in the actual duty cycle generated by the control of the power electronic unit.

(Figure 3-88)

This is a typical example of one of the recharge curves with the battery in a flat condition. We go through approximately 17 orbits before the third-electrode signal will turn on the relay to provide power to the HEPPS system.

(Figure 3-89)

You will notice at 35°C that we acquire no load current, because the battery voltage is low at this time.

(Figure 3-90)

This vugraph is at the other extreme, or at minus 30°C. In this case we see that the dump circuit becomes active after approximately 14 orbits, and the third electrodes are out around 32 orbits or so before the second or third electrode would activate the load relay to the HEPPS experiment.

(Figure 3-91)

One thing I would like to point out on that last vugraph is the fact that during this charge, we simulated the expected solar array, instead of using a constant current or type charge of that nature.

Four photographs were taken of the system during the final assembly process. The first photograph shows a structure within a structure. This is the tray of the LDEF, and our structure is inside of the tray. This was done because directives specify that we mount to the tray using the bottom mounting surface only for equal load distributions and thermal design.

Our input to the spacecraft is through the slots located up to the top right for connector mounting.

(Figure 3-92)

This is the next step in the process where we have mounted a thermal blanket completely to the inside. We have some rigid requirements not to pull heat from the spacecraft and not to dump any heat into the spacecraft. I think they are working in the range of 5 to 10 watts. So we mounted a thermal blanket over the entire inside of the surface.

(Figure 3-93)

The third photo was taken on the top plate of the power system which contains all the electronic components. In the center we see the battery. We have a feeder flow mounted directly to the battery that I mentioned previously.

The power electronic unit is mounted to its right with the cabling actually going through the plate to interface with the solar panels on the other side. This plate is made out of 3/4-inch aluminum and is approximately 30 by 30 inches. This type plate was used to provide the thermal control that we need plus the thermal – I mean the structural strength that we needed in the verification.

Eight 1/2-inch square fiberglass spacers, G-10 spacers, are used to mount this plate on to the internal structure, again, for the thermal isolation required of our experiment.

(Figure 3-94)

This last photo was taken of the completed system in which case you can now see the four solar panels to the right to the top of the tray. The top surface has been painted green. This is a special thermal paint to allow for the best thermal conductivity throughout the plate.

The goal of the design was to provide a power system that would provide sufficient power to the HEPPS experiment. A system that would operate completely automatic from time of launch to time of retrieval. And a system that would operate in the near-Earth gravity gradient orbit without detrimental degradation due to the temperature environment.

## DISCUSSION

NAPOLI: In one of the first vugraphs, you had an indication that the main battery system for the LDEF was discharged, and then was subsequently charged after being released from the shuttle. Is that some sort of a safety requirement that was imposed upon you by the shuttle operation people? Or, was that something that you elected to do?

TILLER: Because the astronauts were on board the shuttle, they would desire the battery to be in the discharged condition both during launch and retrieval.

During launch it was very easy for us to start with a discharged battery and let the battery charge once it obtained its orbital position.

During retrieval it was a lot harder to discharge a battery. So we have to live with the fact that the HEPPS experiment will be removed from the main bus during retrieval by the LDEF spacecraft itself.

NAPOLI: Is there some sort of general safety requirement for all shuttle payloads that you may be aware of that requires this?

TILLER: I am not sure what the requirements were. What we tried to do was provide as much safety as possible with our experiment. I am not familiar with what the real requirements are, except the fact that during our design review, they bought the fact that we would launch in that condition. It just provides adequate safety. I am not familiar with other experiments on the LDEF for future shuttle missions.

FORD: Joe, if I might add to that, there is another driver here, and that's launching in the condition we are in. This LDEF configuration has quite a long time period in which you don't have access to it prior to launch, and I don't know whether it is like 4 to 6 months. But once delivered, we have no way to get back into it.

So this mode of launch in the discharge condition was chosen to minimize the unknown effects of that long exposure in this environment. That was the main driver.

TILLER: They gave us a maximum time period of 10 weeks, up to 6 months.

HARKNESS: Sid, did your tests at  $-30^{\circ}\text{C}$  immediately follow those at  $35^{\circ}\text{C}$ ?

TILLER: I don't remember the exact sequence of the four tests we ran at minus 30, minus 15; I believe it was zero and plus 35. I think once we were cold, we probably ran the cold tests and then the hot. But I don't remember offhand which sequence we went through.

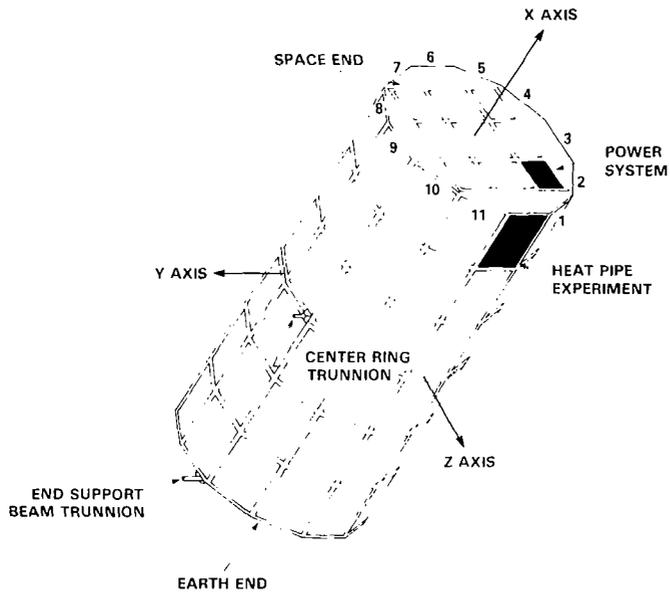


Figure 3-83

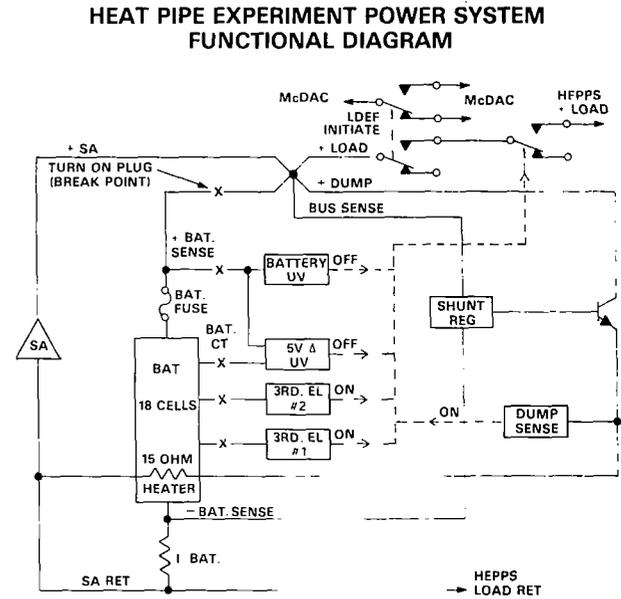


Figure 3-84

BATTERY CHARGE/DISCHARGE CHARACTERISTICS VS EXPERIMENT DUTY CYCLE

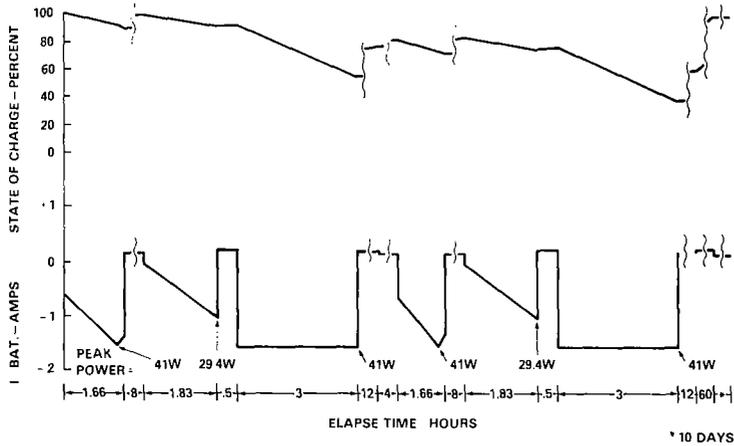


Figure 3-85

AVAILABLE BATTERY CHARGE CURRENT VS PSEUDO LATITUDE

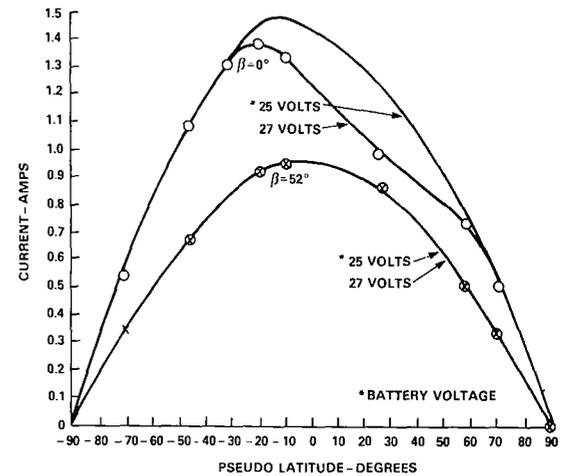


Figure 3-86

### BATTERY TEMPERATURE VS ORBIT TIME

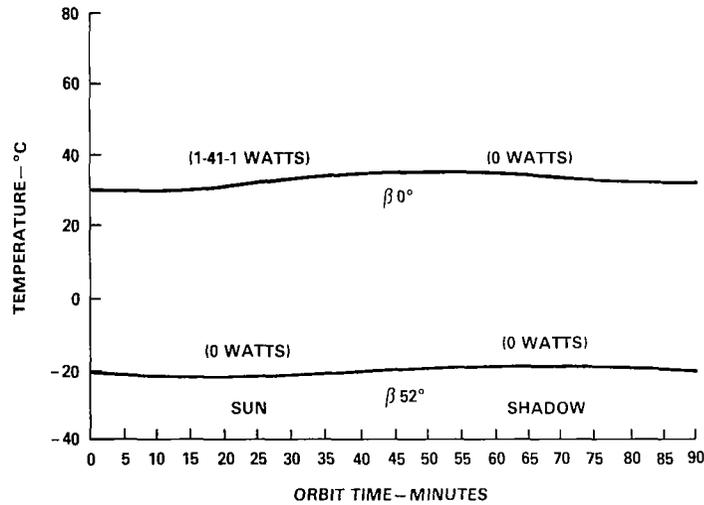


Figure 3-87

### BATTERY VOLTAGE CHARACTERISTICS VS CAPACITY (2 AMP DISCHARGE RATE)

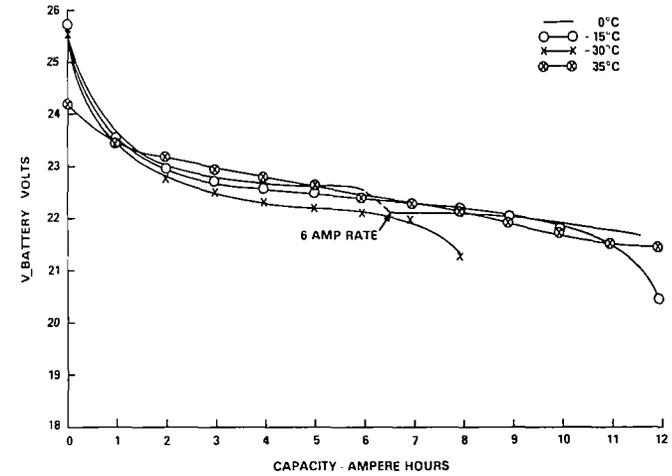


Figure 3-88

### POWER SYSTEM BATTERY CHARGE CHARACTERISTICS AT 35°C

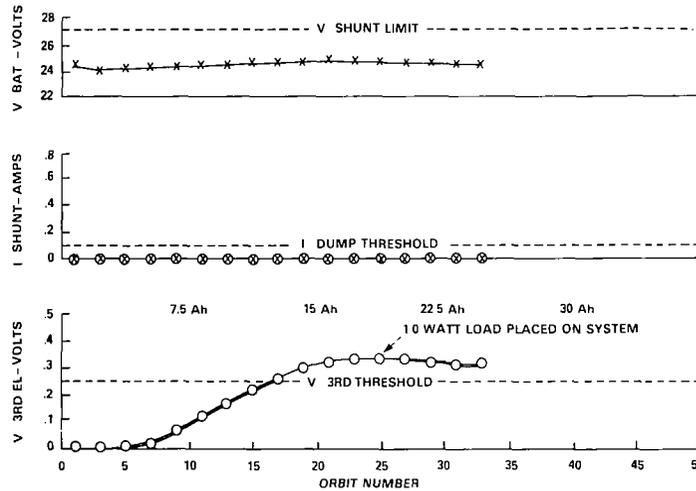


Figure 3-89

### POWER SYSTEM BATTERY CHARGE CHARACTERISTICS AT -30°C

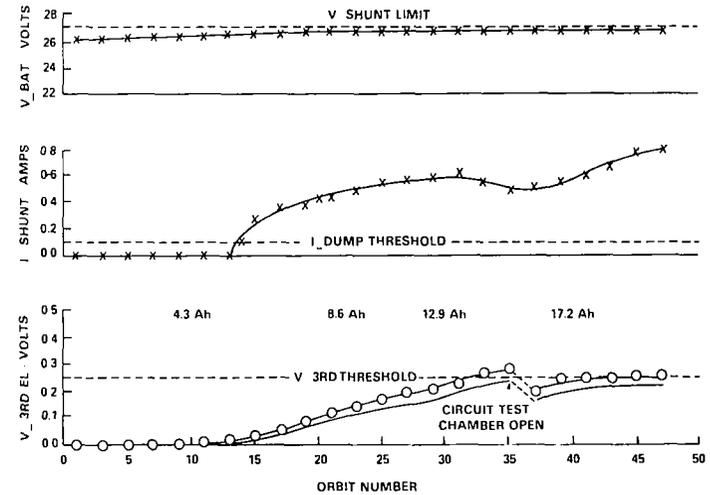


Figure 3-90

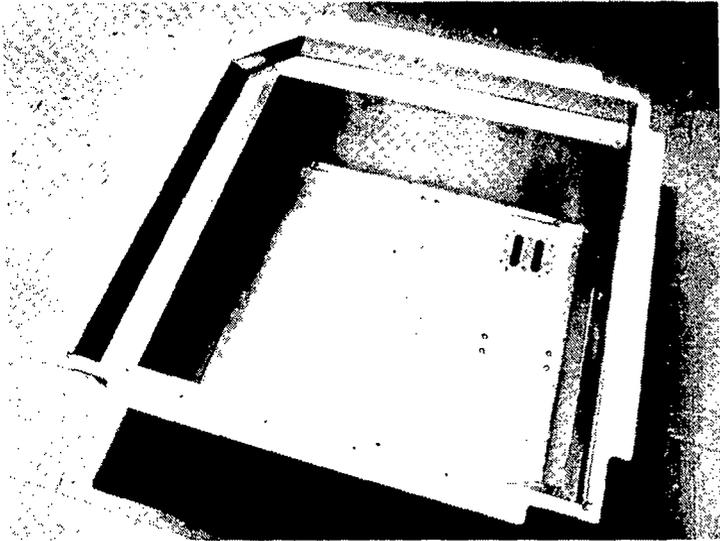


Figure 3-91

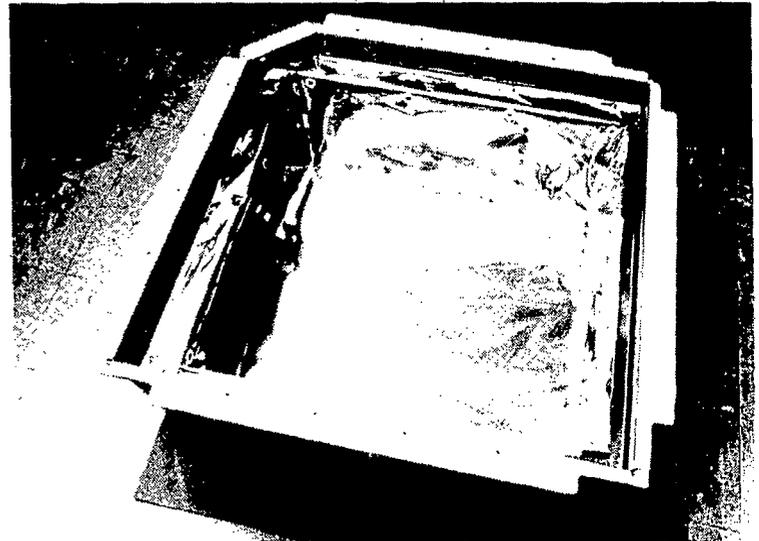


Figure 3-92

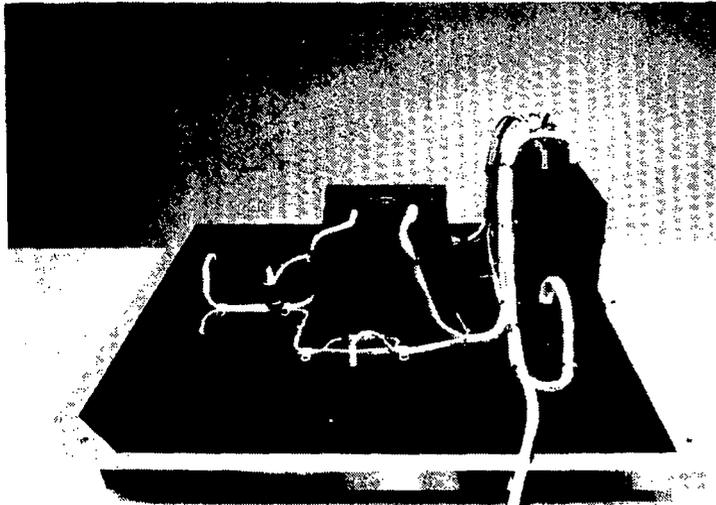


Figure 3-93

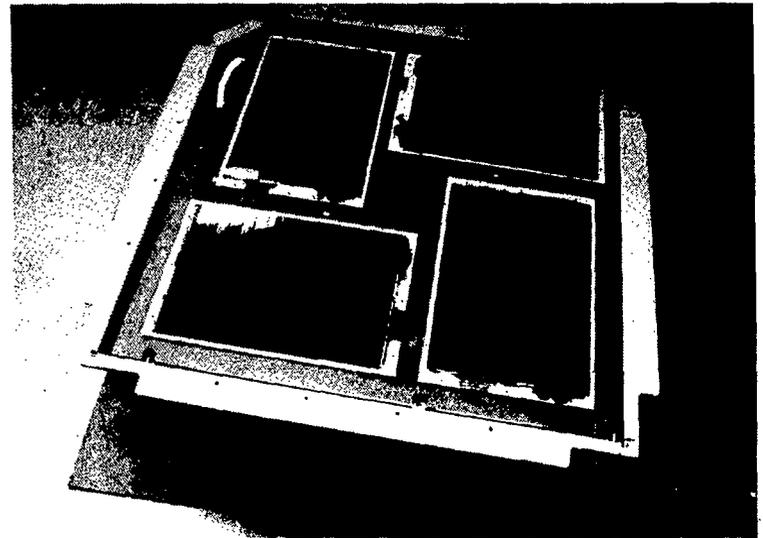


Figure 3-94

SESSION IV

BATTERY AND CELL TESTING

J. Harkness, Chairman  
Naval Weapons Support Center



## 20 WATT-HOUR PER KILOGRAM NICKEL CADMIUM ENERGY STORAGE FOR INTELSAT V

J. Armantrout  
Ford

I would like to talk today about the nickel-cadmium battery that we have on the I-V program. We are speaking in terms of 20 watt-hours per kilogram usable energy density. If we go to 100 percent DOD, we have a system that is probably around 40 watt-hours per kilogram. We are talking in terms of a 7-year battery, and that is the reason for the use of the 20 watt-hours per kilogram.

(Figure 4-1)

This is the battery assembly. The cells are on their sides. It is the T-rib. We have the T-ribs, four cells on one T-rib. The T-rib is the heat sink to the baseplate.

(Figure 4-2)

With this next slide, we can see the end-view. We have heaters on every four cells, 28 watts of heaters. We have a power connector and a cell sense. We have a capability in orbit of monitoring and cell voltages. That's a nice feature we have.

(Figure 4-3)

On our battery configuration performance characteristics, we have a nominal battery load we are showing here, of 504 watts. That's now about 465 watts. Our nominal discharge current at 33.6 volts was 15 amperes. At the beginning of life, we will probably have about 34.2 volts, and that would be about 13.6 amperes.

Rated cell capacity is 34 ampere-hours, and our maximum design DOD is 55 percent. Right now, the actual depth is about 51, and with one cell failed with our diode bypasser, that drops down to about 48. Or rather, we are at 48-percent DOD, and with one cell failed we will go to 51.

Typical synchronous orbit maximum discharge is 1.2 hours, and our peak discharge current is 45 amperes. We are recommending bisequence charging. Our full charge rate that we are looking at right now is in the range of 2.26 to 2.86 amperes. We have a capability of going to higher charge rates or lower.

Trickle charge is in 0.73 to 0.95 range. We are looking at a 7-year life, 616 cycles. We also have electrothermal thrust of firing that occurs during the sunlight periods, which could add a potential 175 cycles to that number which would be 791 cycles in 7 years.

Our allowable temperature range is 1 to 25°C. Right now, our thermal predictions are that we will be operating at 1 to 16°C.

(Figure 4-4)

Some of the design characteristics of the cell are positive electrode, 13 plates, and loading of about 13.4; negative electrode, 14 plates with a loading of about 15.7. These are GE cells. Separator materials, nylon 2505. Our electrolyte is 31 percent by weight. KOH approximately 90 milliliters.

Our cell container is 304L stainless steel, 0.03 centimeters. Our negative electrodes are impregnated with TFE.

(Figure 4-5)

The weight of the case is approximately 80 grams. Positive and negative electrodes are 767, separator 17, KOH about 114. We got about 1025 grams. This is the cell weight. This is a nominal 34 ampere-hour. We are getting about 37 out of it.

(Figure 4-6)

The total weight on the engineering model battery, 28 cells, was about 31.6. Now, that was without our diode bypass. Diode bypass circuitry, which I will show in a later picture, adds about 0.9 kilogram so that number comes up to around 32.5 kilograms for the battery weight. This is the number that we use when we come up with a 20-watt-hours per kilogram usable energy density and 40-watt-hours per kilogram actual.

We are indicating corner blocks here, and I will show you in a minute, those corner blocks are not on the assembly now.

(Figure 4-7)

Our designs traditionally had a corner block that was epoxied on in this area of each four-cell group. These are now machined into the T-ribs, and it's an integral part of the T-rib.

Here you can see the diode assemblies which are mounted – actually they are part – the bolts that bolt the T-ribs into the platform also hold down the diode bracket. And we have protection in both the charging direction and the discharging direction. So, if we have an open cell failure for any reason, we can continue to operate.

(Figure 4-8)

Some of our flight battery test summary data is here. This is our initial reconditioning, or actually our first capacity test after our initial reconditioning cycles. We were getting around 37 ampere-hours, peak battery voltage around 41.2, or thereabouts. Our maximum cell voltages are as shown here. Our zero-degree capacity is about 33 on this particular cell lot and is running a little better here, about 35, 36.

These are our flight 1 batteries, and these are our flight 2 batteries. Vibration voltage stability running around 0.2 volt.

This is thermal vacuum. This is just a functional test during thermal vacuum. It is not a capacity test or anything of that sort.

We do a pulse load test which is 45 amperes, and this is the voltage performance we are getting, about 33-1/4 volts.

Then, after we have done all of our battery environmental tests, we turn around and do another room-temperature capacity. You can see the capacity is improving with time. This appears to be a characteristic of the teflonated negatives. As you begin to cycle these cells and get some life on them, the capacity is improving.

We have life testing underway. We have three batteries and have an accelerated life test, three cycles a day, a maximum eclipse 1.2 hours at 15 amperes. We recharge at 6.8 hours, about 3.2 amperes, 120 percent energy return.

We have completed 14 seasons on that particular test. We are not seeing any voltage degradation, except for when we do our capacity measurements after every second season. There is some tailoff of the voltage as you are about 90 percent into the discharge of a battery. Otherwise, the voltage is flat. It looks the same as it did at the beginning of life.

Our semiaccelerated test has got four eclipse seasons completed. That consists of a real-time eclipse profile, 2 weeks of sunlight simulation, and then our real-time test. We have completed two eclipse seasons, and we are into the second solstice, which is a 135-day simulation.

That pretty much concludes the status of where we are at on this program right now. We have, in fact, a replacement system that we are looking at, which will be the nickel hydrogen. Gert Van Ommering will be talking about that tomorrow.

We are going both ways. We have an option to go either nickel cadmium or nickel hydrogen. The first four flights will be nickel cadmium. Flights five through eight right now can be either nickel cadmium or nickel hydrogen.

## DISCUSSION

**NAPOLI:** Can I ask some questions of Armantrout? Do you have constant power discharge on the batteries? I am talking about what's intended for the flight.

**ARMANTROUT:** The flight will be constant power, and 465 watts is the number right now. That has been varying as the loads – I believe that is the most current number. I showed 504 on the vugraph.

NAPOLI: Do you plan to do any reconditioning?

ARMANTROUT: We plan to recondition every eclipse season prior to it.

NAPOLI: To what level?

ARMANTROUT: Right now, we are in the life test. We are going down to the first cell, to 0.7 volt. Some of that it still being worked out. I don't know that we have a final plan there.

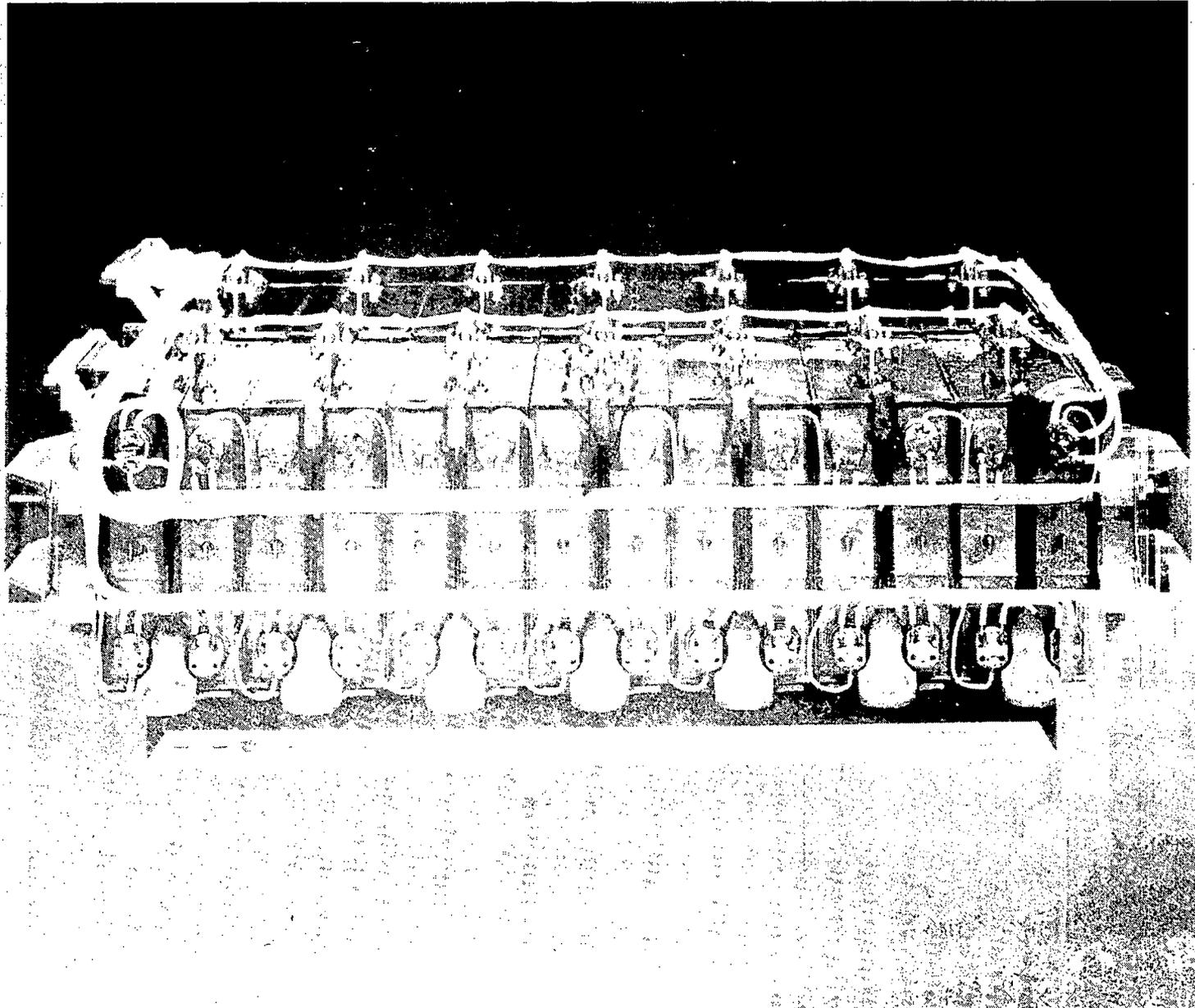


Figure 4-1

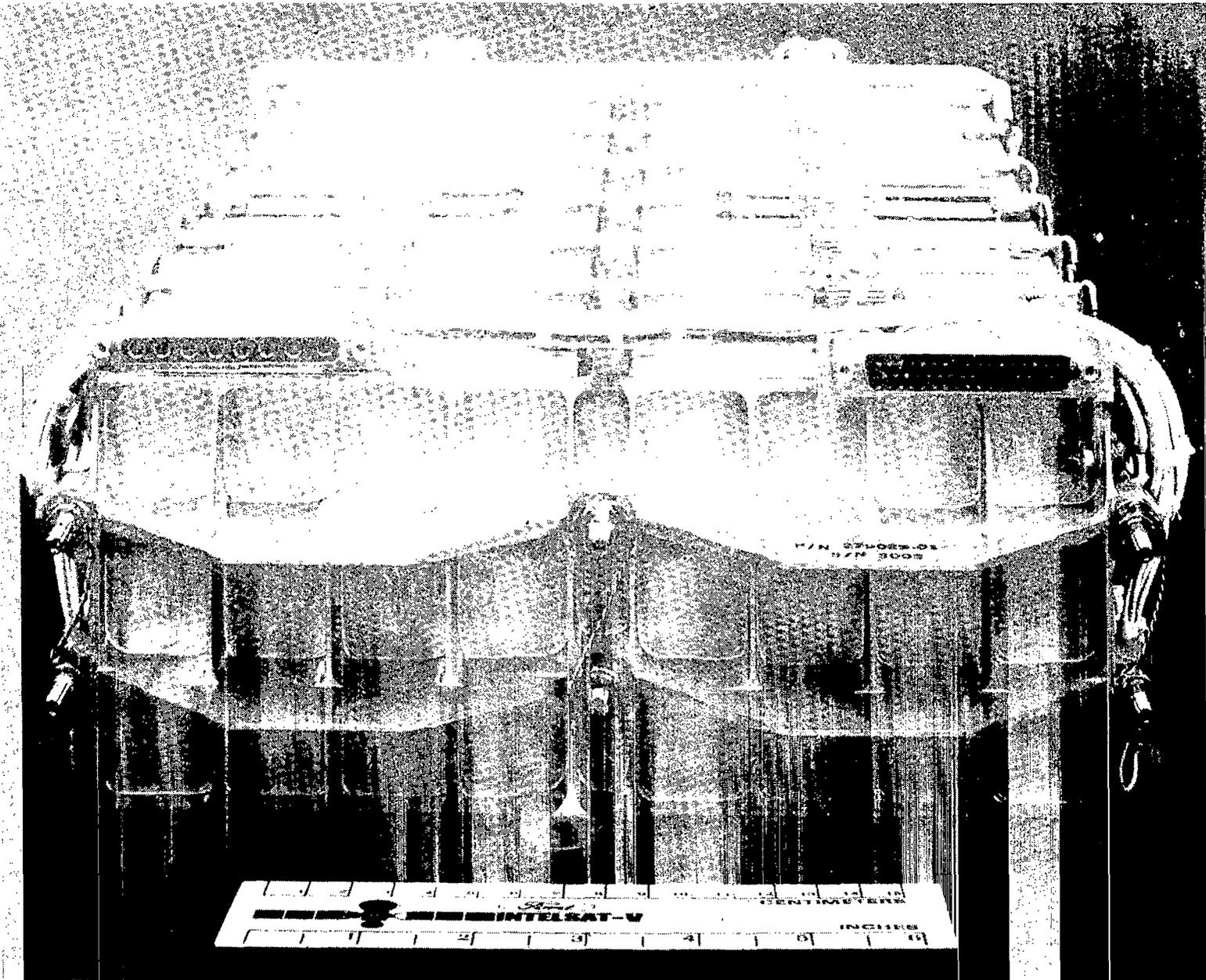


Figure 4-2

## BATTERY CONFIGURATION PERFORMANCE CHARACTERISTICS

• NOMINAL BATTERY LOAD PER BATTERY	504 W
• NOMINAL DISCHARGE CURRENT AT 33.6 VOLTS	15.0 A
• RATED CELL CAPACITY	34.0 Ah
• MAXIMUM DEPTH OF DISCHARGE	55%
• MAXIMUM DISCHARGE TIME	1.2 h
• PEAK DISCHARGE CURRENT (10 SECOND PERIOD MAXIMUM)	45.0 A
• ALLOWABLE SEQUENCE CHARGING CURRENT RANGE (FULL) (TRICKLE)	2.26 TO 2.86 A 0.73 TO 0.95 A
• TOTAL ECLIPSE CYCLES (7 YEARS)	616 CYCLES
• ORBITAL LIFE	7 YR
• ALLOWABLE BATTERY TEMPERATURE RANGE DURING ORBITAL OPERATION	-11 TO +25° C

Figure 4-3

## CELL COMPONENT DESIGN CHARACTERISTICS

• POSITIVE ELECTRODE	13 PLATES, 10.4 cm x 9.8 cm x 0.69 mm LOADING: 13.40 ± 0.6 g
• NEGATIVE ELECTRODE	14 PLATES, 10.4 cm x 9.8 cm x 0.74 mm LOADING: 15.70 ± 0.65 g
• SEPARATOR MATERIAL	NYLON 2505 ml
• ELECTROLYTE	31% BY WEIGHT KOH SOLUTION. ELECTROLYTE QUANTITY: 88 – 90 ml
• CELL CONTAINER	304L STAINLESS STEEL SHEET: 0.030 cm THICK
• NEGATIVE ELECTRODE ADDITIVES	TFE: 0.35g/dm <sup>2</sup>

Figure 4-4

## CELL COMPONENT WEIGHT CHARACTERISTICS

COMPONENT	WEIGHT
CASE	80.4 g
POSITIVE AND NEGATIVE ELECTRODES	767.4
SEPARATOR	17.6
WRAPPER	3.9
KOH	114.5
COVER	40.3
COMB INSULATOR	1.3
TOTAL	1025.4 g

Figure 4-5

## ENGINEERING MODEL BATTERY WEIGHT BREAKDOWN

COMPONENT	WEIGHT
BATTERY CELLS (28 EACH)	28.71 kg
ENDPLATES (2 EACH)	0.54
TIE ROD ASSEMBLIES (6 EACH)	0.27
CELL SUPPORT RIBS (7 EACH)	1.19
CORNER BLOCKS	0.02
CONNECTORS, HEATERS, THERMISTORS	0.13
WIRE, EPOXY, SHRINK TUBING, AND MISCELLANEOUS	0.73
TOTAL	31.59 kg

Figure 4-6

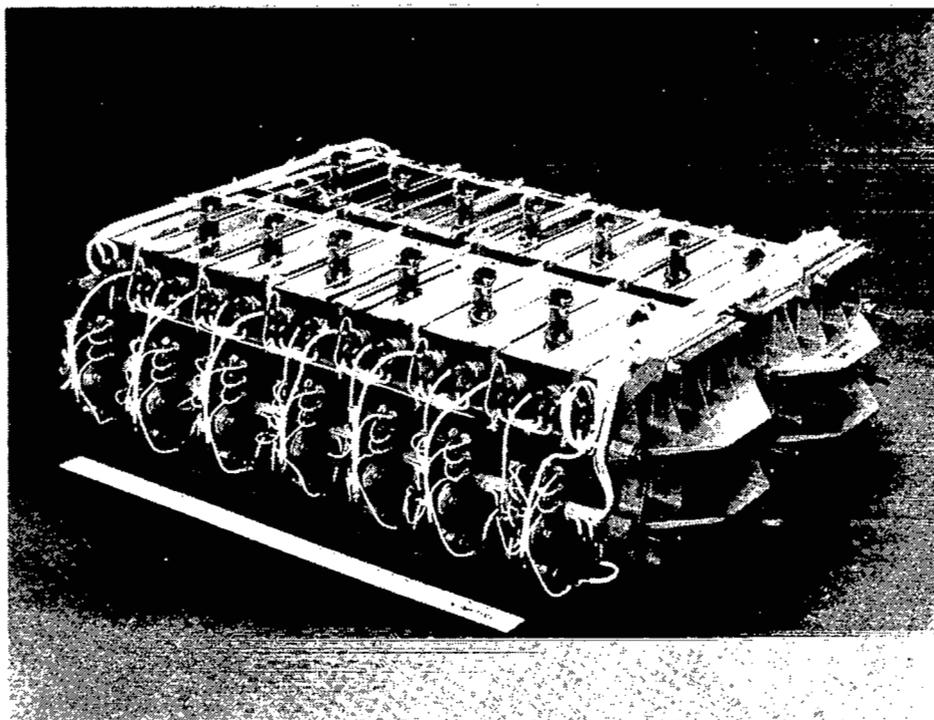


Figure 4-7

### INTELSAT V FLIGHT BATTERY TEST SUMMARY

TEST	BATTERIES	RESULTS			
		3006	3007	3008	3009
20°C	CAPACITY	37.20 Ah	37.20 Ah	37.05 Ah	37.35 Ah
	BATTERY VOLTAGE	41.27 V	41.20 V	41.61 V	41.67 V
	MAX CELL VOLTAGE	1.476 V	1.476 V	1.478 V	1.484 V
0°C	CAPACITY	33.30 Ah	33.00 Ah	36.15 Ah	35.85 Ah
	BATTERY VOLTAGE	42.36 V	42.45 V	42.77 V	43.05 V
	MAX CELL VOLTAGE	1.518 V	1.526 V	1.539 V	1.528 V
VIBRATION VOLTAGE STABILITY		0.23 V MAX	0.16 V MAX	0.10 V MAX	0.28 V MAX
THERMAL VACUUM					
20°C	DISCHARGE BATTERY VOLTAGE	35.65 V	35.57 V	35.71 V	36.15 V
20°C	CHARGE BATTERY VOLTAGE	38.42 V	38.25 V	38.11 V	38.61 V
PULSE LOAD BATTERY VOLTAGE		33.25 V	33.15 V	33.84 V	33.88 V
20°C	CAPACITY	39.00 Ah	38.40 Ah	40.35 Ah	40.35 Ah
	BATTERY VOLTAGE	42.00 V	41.54 V	42.04 V	41.73 V
	MAX CELL VOLTAGE	1.496 V	1.485 V	1.504 V	1.494 V
CHARGE RETENTION (MINIMUM CELL VOLTAGE)		1.213 V	1.221 V	1.203 V	1.212 V

Figure 4-8

## MULTIMISSION MODULAR SPACECRAFT PARALLEL BATTERY TEST

M. Tasevoli  
NASA/GSFC

For the past two workshops, Charlie Palandati has been presenting the results of the engineering evaluation of the multimission modular spacecraft performed by the Power Applications Branch at NASA.

(Figure 4-9)

Today I will present additional test data on the results of several simulations which were repeated after approximately 10,000 orbits to further characterize the operating stability of the power battery operation.

(Figure 4-10)

The multimission spacecraft power system employs a standard power regulated unit with eight commandable voltage temperature levels charging up to three standard 20- and 50-ampere hour batteries in parallel. The mission requires a depth of discharge of 25 percent per battery in the near-Earth orbit of 100 minutes; 36 shadow, 64 sunlight.

The 12-ampere hour batteries used for the simulation utilize a standard electrical approach of 22 cells in series and a thermal design which is an extension of the IUE spacecraft battery and which has been further instrumented to record cell pressures and temperatures. Both batteries are mounted on a thermal cooling plate with a circulating refrigerant and are installed in two separate forced air chambers.

(Figure 4-11)

The first test performed within the first 2000 cycles was an evaluation of four of the eight VT levels. In particular, we were evaluating the battery charge response within the design temperature range of 0 to 20°C.

Based on those results at that time, level 5 supported both batteries with nominal depth of discharge of 25 percent with a percent recharge between 101 and 105 percent within the design temperature range of the module. Based on those results, level 5 was chosen as a baseline level for the entire program when not in a test simulation.

This test was repeated at level 5 after 11,000 orbits at those three temperatures. Of particular significance is, there is very little difference in percent recharge and load sharing between the batteries when comparing the two results.

Cell pressures have approximately doubled during the period as a result of this cycling. There is a slight increase in the end of charge current, but, on the whole, the batteries continue to share the load quite evenly.

(Figure 4-12)

One of the power system design criteria is that the battery cable harness shall be less than 150 milliohms. However, there is no specification on mismatch.

The purpose of this test was to simulate an ohm-resistance mismatch between cables and to determine the effect of load sharing on the parallel battery configuration. Every effort initially was made to ensure that the in-cell connections and the power cables were properly matched. In particular, the battery impedance was determined by assuming approximately 3 milliohms per cell and calculating 9 milliohms for all the in-cell connections up the battery post, here represented by 75 milliohms for A and B.

The measured A and B cable resistances, which included not only the wiring harness but the connectors and the shunts, were measured at 76 and 77 milliohms, respectively, up to the parallel tie point. Cable mismatches will be simulated now by inserting a nonresistive shunt in the B circuit leg.

(Figure 4-13)

These results are tabulated here, highlighting the individual battery C/D ratio and the depth of discharge. Notice that the increasing resistance of one leg resulting in a divergence of the depth of discharge with the battery, in this case battery B, with the longer path length supporting less of the load on discharge. In contrast, the battery C/D ratios remain essentially unchanged.

(Figure 4-14)

The simulation was again repeated after the cable resistances were lowered by approximately 87 percent from 77 to 10 milliohms. Here again the battery impedance was assumed to remain the same, 75 milliohms, and the cables were lowered to 10 milliohms each.

As before, I have gone ahead and compared again individual C/D ratios and depths of discharges for both batteries. I have gone one extra step by comparing the results at similar mismatches for both the high- and the low-cable resistances.

Notice that in the last three trials performed with the lower cable resistance, the effect of the cable mismatch has rather a negligible effect on the depth of discharge while the C/D ratio again remains unchanged.

The results also seem to indicate that as the battery impedance becomes a greater portion of the circuit resistance, cable mismatches become less significant.

(Figure 4-15)

The last simulation performed was that of simulating one shorted cell in one battery. The simulation was conducted in basically two stages.

The first stage found one cell in Battery B would have a 1-ohm resistive load placed across it, while the parallel batteries continued to cycle. In the second stage, as the cell voltage dropped to below 0.5 volt, the resistive load would be replaced with a hard short, as the batteries are allowed to continue to cycle. In the interim, all battery characteristics are monitored to observe system stability.

It should be pointed out that during that first stage with the resistive load across the cell, as long as the cell supported some voltage on discharge and charge, it was very nearly impossible to identify any system anomaly throughout the period where the cell supported some voltage on charge and discharge.

(Figure 4-16)

The most dramatic change occurred when the resistive load was replaced with the hard short here at the end of the discharge cycle, here numbered at cycle 1.

Within less than one orbit, the recharge ratio on the shorted cell battery increased from a nominal 1.05 to 1.7 as cell pressures increased from 30 to approximately 75 psi, as the end of charge current increased from a nominal 0.5 ampere to slightly less than 3 amperes.

After an additional orbit, you will notice that the battery B remains in the sump state of condition experiencing a possible thermal voltage instability. In contrast, battery A is experiencing normal, near-normal recharge as the end of charge current tapers off normally while sharing approximately 60 percent of the load on discharge.

(Figure 4-17)

This is a comparison plot of cell characteristics, most notably voltage, current, and pressure as a function of time, approximately 40 orbits after lowering the charge level from 5 to 3. You will see that for the shorted cell, battery, the recharge ratio dropped considerably from 1.6 to 1.15 as the cell pressures dropped from 90 to 95 range down to below 50 psi. In contrast, battery A with 22 normal cells is experiencing a recharge ratio of 0.99 while supporting approximately 60 percent of the load on discharge.

Notice that while the individual battery voltages are tracking very nicely on discharge and charge, the individual battery currents are diverging quite noticeably.

(Figure 4-18)

A simulation at level 3 was continued for approximately 440 orbits and was extended another 250 orbits at level 2.

What I wish to highlight in particular is a comparison of load sharing and percent recharge at this lower level. In particular, as highlighted before, Battery A is supporting approximately 60 percent of the load on discharge, whereas battery B has a significantly low amount.

Battery A throughout that first 400 orbits is experiencing approximately a recharge ratio of 0.99. Battery B with the shorted cell supporting less of a load has its percent recharge increase quite dramatically from 1.15 up to nearly 1.5. This is the second time that the shorted cell battery has experienced some type of thermal voltage instability. Additionally, the pressures on battery B also increase with the increasing C/D as was the end of charge currents.

In response to this unstable condition of battery B, the charger level was further reduced from three to two, resulting in a lower recharge ratio for both batteries. Now, the shorted cell battery experienced a gradual decreasing C/D ratio while battery A was at approximately 97.5 percent recharge.

It is also interesting to note that there is a reversal in the load sharing after switching from level 3 to level 2. Prior to this time, the 22-cell battery was supporting most of the load. After switching from 3 to 2, now the shorted cell battery is experiencing the greater depth of discharge.

(Figure 4-19)

The test was terminated arbitrarily by extending the discharge cycle to simulate an extended eclipse to determine the actual capacity available to the load. Highlighting battery voltage and battery current as a function of time in orbit, you will see that battery A running down, the state of charge delivered approximately 8.6 ampere-hours when its lowest cell dropped below 0.5 volt.

At that time, battery B delivered approximately 9.4 ampere-hours and was further discharged to 11 ampere-hours when battery A was removed from the line. The uneven load current is a clear indication of the two battery imbalances that were simulated during this extended period. That is a cell imbalance between the batteries and also a capacity imbalance with the 22-cell battery at below 100-percent recharge, essentially running down the state of charge.

(Figure 4-20)

After the shorted cell simulation, the hard short was removed, and the cell voltage recovered quite normally. As in all our tests, we immediately reestablish the baseline cycling at level 5 and 25 percent of discharge. Almost immediately the batteries began to share the load unevenly, favoring battery A at 26 and battery B at 24.

The C/D ratio of the shorted cell battery increased steadily for approximately 250 cycles as the recharge ratio increased from 1.07 to 1.15.

At approximately 250 cycles, several cells in battery B exceeded the software limit established for the test. The software limit at 10°C was 1.51 volts per cell. At this point and without changing the loads on the system, the charger level was reduced from 5 to 3.

Cycling has continued for approximately 1200 orbits now as both batteries are experiencing approximately 99 percent recharge.

(Figure 4-21)

In conclusion, the voltage versus temperature levels that are built into the MPS system has sufficient versatility to accommodate a wide range of abnormal conditions. In particular, during the shorted cell simulation, it was impossible to identify the partially shorted cell condition from telemetry data.

In contrast, for the hard-cell short level 5, the shorted cell battery experienced a severe overcharge exceeding the high end of charge currents, while supporting less of a load on discharge.

In an actual spacecraft environment, the battery temperature would increase quite rapidly and probably trip the overtemperature thermostat.

With the added versatility of additional lower levels, it was demonstrated that, indeed, a short-term stable operation could be sustained for several hundred orbits without changing load currents.

Increasing the impedance mismatch between battery harness cables resulted in a divergence in the depth of discharge while the recharge ratio remained unchanged.

Cable mismatch has a less significant effect on parallel battery performance, as the battery impedance becomes a more dominant or predominant part of the circuit leg impedance.

## DISCUSSION

LEAR: With the 1200 cycles continuing running at less than 100-percent state of charge, how long do you expect to run that test before you deplete all the energy in the batteries?

TASEVOLI: I would like to answer the question this way: Although a percent recharge was below 100 percent, the watt-hour efficiency was greater than 100 percent. In particular, at 99-percent recharge, the watt-hour efficiency was approximately 108 percent.

And at the lower percent recharge, 97.5 at level 2, the watt-hour efficiency was again greater than 100 percent. I think it was approximately 104 percent.

I would like to answer that question specifically. I had the same question in mind, too. I attempted to determine the actual capacity lost if the battery is experiencing a 99-percent recharge.

In particular, I went ahead and I plotted orbits on the X-axis, and what I will term here as just cumulative lost ampere-hours.

The solid lines represent three different trials where we purposely placed the battery in such a condition as the percent recharge was below 100 percent. For these three trials, the percent recharge was 99 percent. These solid lines then will represent the cumulative lost ampere-hours as simply the difference between ampere-hours in the ampere-hours out at each cycle and summed over several hundred cycles.

In particular, these two small lines show that the battery was run at 99 percent recharge, and the test was terminated with an extended discharge after about 240 orbits. The capacity lost based on the rated capacity was almost 2 ampere-hours.

The same analysis could be done during the 800 orbits in the shorted cell simulation where, for the first 440 orbits, battery A was experiencing a percent recharge of 99 and when switched over to level 2, considerably less, approximately 97. That point then is right here, 8.6 minus 12 or slightly under 4 ampere-hours lost. Based on these calculations then, it could be possible that we could be in this particular mode for several thousand cycles.

PALANDATI: I would like to clarify one thing right now. These tests started last November. The purpose of the tests are for the fact that actually there were certain conditions in a spacecraft, at that point the voltage level would automatically decrease. Should the temperatures get to a certain point you would automatically drop down to these lower levels.

Of course, the first question was: Could you maintain the two batteries or three batteries in a parallel application at the lower level?

We ran a test for approximately 1 1/2 months, and as we added the ampere-hours in versus the ampere-hours out, nice numbers, we suddenly said we shouldn't have more than 3 ampere-hours left in any one of the two batteries. We ran a CAP test and said the CAP test told us we had better than 8 ampere-hours.

There is no definite explanation of it other than the fact that we looked at the watt-hour relationships, the energy that does go into a battery and comes out of the battery, we were always on the plus side.

Mike continued on again in January and February running some more tests, and the longer he ran it the longer the batteries continued to go, even though our numbers said we have two dead batteries. We still had power. That was basically the reason for the test to start with, to see whether we could definitely operate two batteries at the low level, particularly if you did have one, say, with a shorted cell.

THIERFELDER: On the hard short case you showed after two cycles, you were up charging at 3 amperes, on a C/4 rate, and the pressure was up to 95 pounds. Suppose you hadn't switched to level 3 at that point? Would the cell have blown up?

TASEVOLI: Remember in an actual spacecraft environment, in the thermal vacuum conditions, at this particular C/D ratio of over 1.5, I suspect that the battery temperature would exceed the overtrip temperature.

THIERFELDER: You are gambling on what comes first, the temperature rise or the pressure rise.

TASEVOLI: The test condition, the limits on a test condition, was to take some type of action. If the cell pressure went above 100 psi, that was our governing factor during this isothermal test, to do something. Either lower the loads, or in this particular case, we decided to lower the charger level.

THIERFELDER: So, in orbit, someone would have to be watching every orbit to do the same thing. To do what you did on your test in orbit, someone would have to change from level 5 to level 3.

TASEVOLI: I was under the impression that the overtemperature demand was built into the MPS.

THIERFELDER: But you don't know if it is going to go overtemperature.

TASEVOLI: At this C/D ratio and in a thermal vacuum condition, I would think so.

Remember, in this thermal vacuum condition, we purposely kept the thermal condition of the battery at 10°C so that the end-of-charge currents in the C/D ratios here are probably low for the type of condition that we are running.

ENGINEERING EVALUATION OF MMS POWER SYSTEM

OBJECTIVE

- o DETERMINE ENGINEERING LIMITATIONS ON PARALLEL BATTERY OPERATION BY SIMULATING BOTH NORMAL AND ABNORMAL FLIGHT CONDITIONS
- o RECOGNIZE SIGNIFICANT CHANGES OR TRENDS IN BATTERY OPERATING CHARACTERISTICS DURING EACH SIMULATION

Figure 4-9

BLOCK DIAGRAM OF PARALLEL BATTERY CABLE CONFIGURATION

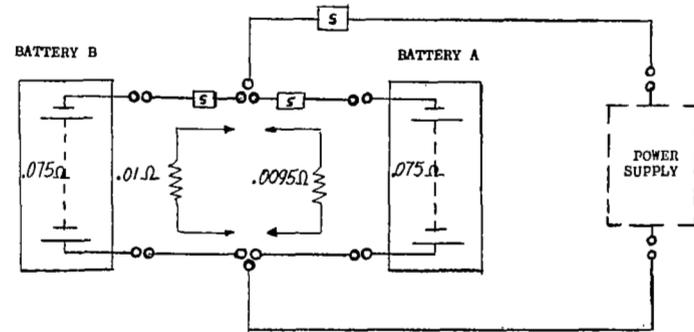


Figure 4-10

BLOCK DIAGRAM OF PARALLEL BATTERY CABLE CONFIGURATION

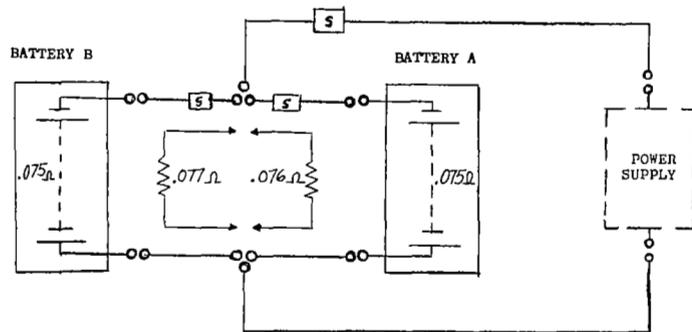


Figure 4-11

**COMPARISON OF BATTERY CHARGE RESPONSE AT LEVEL 5 AND 0° 10° AND 20°C**

ORBIT	TEMP (°C)	EOD VOLTAGE	EOD PRESSURE (PSIA)	EOC PRESSURE (PSIA)	EOC CURRENT (AMP)	C/D
<1000	0	26.84	12.7	13.2	0.56	1.02
	10	27.06	13.6	14.5	0.52	1.03
	20	27.23	11.1	11.6	0.51	1.05
~11500	0	26.53	25.0	26.2	0.66	1.01
	10	26.66	27.5	29.8	0.62	1.03
	20	27.77	28.7	31.9	0.61	1.05

Figure 4-12

## EFFECT OF CABLE MISMATCH ON LOAD SHARING AND C/D RATIO AT V.L.5

% MISMATCH	BATTERY A		BATTERY B	
	C/D	DEPTH OF DISCHARGE (%)	DEPTH OF DISCHARGE (%)	C/D
0	1.04	24.8	25.3	1.02
14.5	1.04	25.2	25.0	1.03
27.6	1.05	25.5	24.7	1.02
40.8	1.05	25.8	24.3	1.03
53.9	1.04	26.2	24.0	1.03
67.1	1.04	26.6	23.6	1.02
132.8	1.04	28.2	21.9	1.02

Figure 4-13

## COMPARISON OF CABLE MISMATCH VS BATTERY CABLE RESISTANCE AT V.L.5

% MISMATCH	BATTERY A	BATTERY B	BATTERY A		BATTERY B	
	POWER CABLE RESISTANCES		C/D	DOD %	DOD %	C/D
0		77	1.04	24.8	25.3	1.02
53.9	76	117	1.04	26.2	24.0	1.03
132.9		177	1.04	28.2	21.9	1.03
0	9.5	10	1.03	25.0	25.3	1.03
57.9		15	1.03	25.1	25.2	1.03
105.3		20	1.03	25.3	25.0	1.03

Figure 4-14

PROCEDURE FOR SHORTED CELL IN ONE BATTERY SIMULATION

- o VERIFY STABLE PARALLEL BATTERY CYCLING AT LEVEL 5 AND 25% DOD
- o CONNECT 1.0 OHM RESISTOR ACROSS ONE CELL IN BATTERY B
- o CONTINUE TO CYCLE AT THE BASELINE OPERATING MODE
- o MONITOR BATTERY CHARACTERISTICS DURING CELL DECAY PERIOD
- o WHEN CELL VOLTAGE DROPS BELOW 0.5 VOLTS REPLACE 1.0 OHM LOAD WITH HARD SHORT AND CONTINUE TO CYCLE
- o OBSERVE LONG TERM CHARACTERISTICS

### BATTERY COMPARISON CHARACTERISTICS DURING HARD CELL SHORT PERIOD AT VL5

CYCLE	BATTERY A					BATTERY B				
	END OF DISCH CURRENT (AMP)	Ahr OUT	C/D	END OF CHARGE CURRENT (AMP)	END OF CHARGE PRESSURE (PSIA)	END OF DISCH CURRENT (AMP)	Ahr OUT	C/D	END OF CHARGE CURRENT (AMP)	END OF CHARGE PRESSURE (PSIA)
1	-7.6	3.3	1.02	0.66	30	-2.4	2.5	1.7	2.9	75
2	-4.9	3.5	1.00	0.75	30	-5.1	2.5	1.6	3.0	90

NOTE: AT THE END OF THE DISCHARGE PERIOD ON CYCLE 1, THE RESISTIVE LOAD WAS REPLACED WITH A HARD SHORT

Figure 4-16

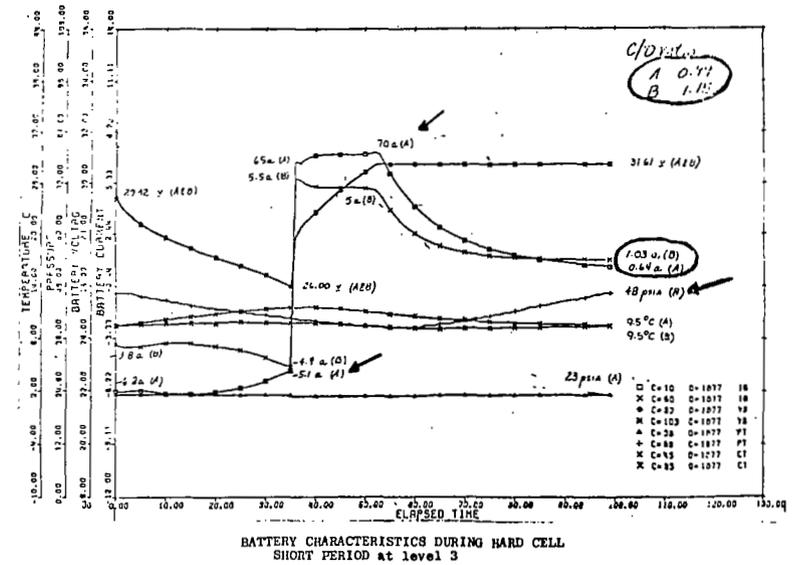


Figure 4-17

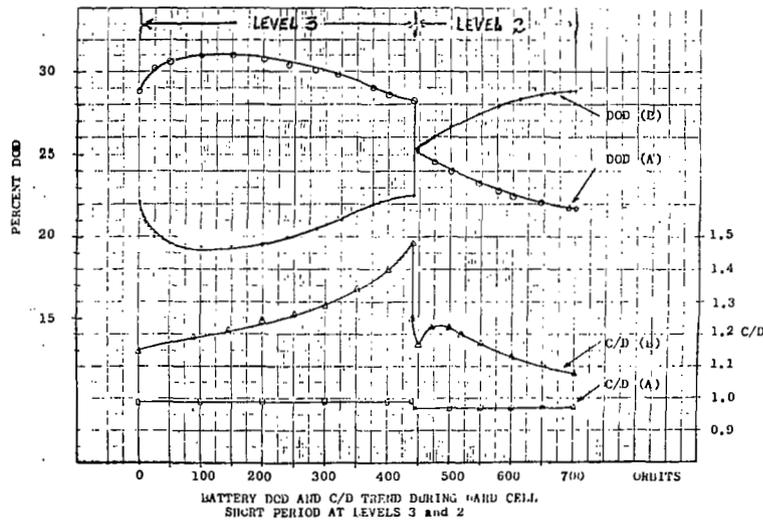
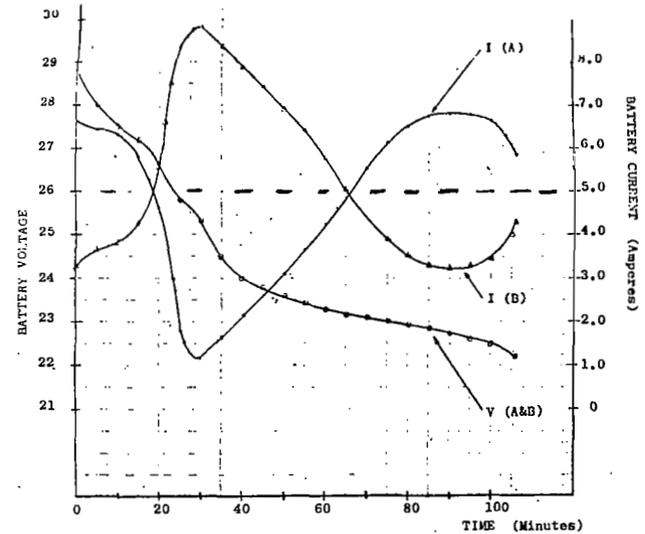


Figure 4-18



DISCHARGE CHARACTERISTICS DURING CAPACITY TEST SHORTED CELL EVALUATION

Figure 4-19

CURRENT UPDATE ON PARALLEL BATTERY CYCLING

- o RE-ESTABLISHED NORMAL BASELINE CYCLING AT LEVEL 5 AND 25% DOD
- o C/D RATIO OF BATTERY B INCREASING DURING CYCLING
- o BATTERIES SHARING LOAD UNEVENLY, BATTERY A 26% AND BATTERY B 24%
- o SEVERAL CELLS IN BATTERY B EXCEED SOFTWARE VOLTAGE LIMIT ON CHARGE AFTER 250 CYCLES
- o LOWER CHARGER LEVEL FROM LEVEL 5 TO LEVEL 3
- o CYCLING CONTINUES FOR 1200 ORBITS AS BOTH BATTERIES EXPERIENCING 99% RECHARGE
- o MISSION DOD REMAINS UNCHANGED THROUGHOUT TEST

Figure 4-20

CONCLUSIONS

- o VOLTAGE VS TEMPERATURE LEVELS OF THE CHARGER HAS SUFFICIENT VERSATILITY TO ACCOMMODATE A WIDE RANGE ABNORMAL CONDITIONS
  - o ACCOMMODATE BATTERY WITH A SHORTED CELL
- o INCREASING IMPEDANCE MISMATCH BETWEEN BATTERY HARNESS CABLES RESULTED IN DIVERGENCE OF DOD WHILE RECHARGE RATIO REMAINED UNCHANGED LOWERING THE CABLE IMPEDANCE RESULTED IN NEGLIGIBLE CHANGE IN DOD AND RECHARGE RATIO

Figure 4-21

## TDRSS BATTERY LIFE CYCLE TESTS INTERIM REPORT

E. Kipp  
TRW

(Figure 4-22)

I am going to be reporting on some life cycle testing we have been doing on the battery that has been designed for the tracking and data relay satellite system. But I would like to first share with you some of the design features of the battery itself.

On the right you will see a colored picture, and actually there are two batteries assembled, as you see on the right, to make up the spacecraft set. In each of the three sections you see, there is a 12-cell battery which is a half battery. When these two batteries are electrically connected in the spacecraft, we connect 12 cells from one battery to 12 cells in the other one to make up actually three 24-cell 40-ampere hour batteries.

(Figure 4-23)

Going around the battery, again we have the three sets of 12 cells each that are interconnected in series. The battery is constructed by making up what we call modified cell assemblies, which is where we take each two cells and we pot it. We first wrap individual cells with glass cloth, and then we pot them to heat sink shims which are L-shaped shims which are then connected to the battery assembly plate that is on the bottom of the battery.

On the cell side of the battery assembly plate, we have heaters. We have a primary heater and a redundant heater. On the space side of the plate, we have second surface mirrors mounted for radiating heat to space. We have thermistors on each end of the battery. There are three on each end, and they are used for battery temperature control, telemetry, indications telemetering the battery temperature, and we also have thermal switches for operating the prime battery heater.

We have a total of seven connectors on the battery. You will see a cutaway of a cover which is, of course, nonflight. We also have in this battery a scanner, which is used for monitoring individual cell voltages in flight.

(Figure 4-24)

This is the component breakdown of the battery. We have 36 cells in each assembly weighing 114 1/2 pounds. You can read down from the top. The end plates are 3.6 pounds and so on. This was the final calculated weight, 138.45 pounds. The qual model battery, which you see on the right, actually comes out to be 138.7 pounds.

(Figure 4-25)

This is a description of the cell chosen for the battery. It's a General Electric cell rated at 40 ampere-hours. The minimum required capacity is 46.6 ampere-hours. Actually, this design was chosen as a scaled-up version of the cell that TRW is flying on the fleet Satcom program.

The reason we chose to scale it up was our experience and also life-cycle testing on that battery, where we had achieved 40 or 42 seasons of life-cycle testing without a failure.

The cell size at 6.6 reaches over the can, 6.6 over the terminals with width 3.4, thickness, 1.3. The weight of the cells is 3 1/4 pounds. The container is 19 mils thick, 304L stainless, and both terminals are insulated from the case.

We have 120 cc's or 31-percent KOH, and some information from the plates is included on the bottom: 16 positives, 17 negative size, or 5.4 by 3.2 by 0.26, 26 mils to 28 mils thick for a positive and 31 to 32 mils for the negative. We do have silver treatment in the negative, and we do not have teflon treatment in the negative.

(Figure 4-26)

This is a brief description on how the batteries are operated in the system. On discharge, the three-battery complement is required to supply 1440 watts for 1.2 hours, which is the mid-season eclipse cycle. That represents a 50-percent DOD for a three-battery operation, and 75-percent DOD for two batteries.

Ordnance loads are estimated to be up to 50 amperes for about 0.13 seconds. We will be reconditioning the batteries before each eclipse season, will be reconditioning them down to approximately 3 volts per battery. The reconditioning will be through one resistor for the entire battery at approximately C/100 rate.

(Figure 4-27)

Now for recharge, the batteries will be allowed to remain on the bus for a few minutes into the sunlight period, so that the batteries will be used to stabilize the cold array voltage down below 40 volts. At that point, they will be removed from the bus.

The TDRSS system will have a dedicated ground system, and it will be manually controlled from the ground at all times. There is no automatic charge control or discharge control anywhere in the system. It is designed to be totally manually operated at all times. This requires somebody to be watching it 24 hours a day, and we hope he will.

After the array warms, the battery will be taken off the bus, and it will be switched on to the full-charged array section. We have dedicated charge array strings, we have dedicated trickle charge strings on each array.

We can adjust the trickle charge by using the reconditioning resistors if we choose, as one method of also controlling battery temperature. We have an onboard automatic protective control system in the event of loss of ground system. If the battery reaches 27°C, there is an automatic switch to trickle charge.

(Figure 4-28)

Our test plan consists of two packs: one 12-cell pack, which we are calling Pack 1; a second 12-cell pack, which we are calling Pack 2; one 50-percent DOD and one we are running at 75-percent DOD.

The 50-percent DOD represents the TDRSS mission simulation, and Pack 1 represents two things. First, we are trying to establish that this cell design truly will be similar as a scaled up Satcom cell; and in the second case, we will be looking at the fact of a one-battery failure mode where we would have to use the two batteries left at 75-percent DOD.

All discharges would be at constant power; recharges at constant current. Then we have dedicated strings on the array. So we can have constant current recharge to a temperature compensated voltage cutoff.

Trickle charging after recharge will be 0.4 ampere for Pack 1; 0.27 ampere for Pack 2. We are controlling temperatures on discharge 15 to 20°C and recharge between 5 to 10°C. Trickle charge from 7 to 10 in one case and 0 to 5 in the other.

I mentioned before the fact that the batteries would be left on the line to stabilize the cold array voltage. So we are simulating that operation by imposing inrush current for the first 10 minutes of each charge period. On Pack 1, of course, it doesn't apply, so we are doing it on Pack 2, cycles 1 and 45. It will be a 6-ampere charge current for 10 minutes. On cycles 21 to 25, it will be 21 amperes, and on all others will be 12 amperes. This will be a constant current.

Our reconditioning will be down, as actually on this test pack, down to about 1 volt, and we will be doing it between each eclipse season. Actually, the simulation will not be simulating the solstice season. It will just be simulating the eclipse season periods.

(Figure 4-29)

These are the two test packs mounted on two heat exchanger plates, thermal control systems. You see here on cell number 6 and on cell number 12 in each pack we have pressure transducers so that we can monitor pressures. We have thermocouples mounted so we can monitor the cell temperature. On the baseplate we have thermocouples mounted so we can control the temperature of the packs.

(Figures 4-30 and 4-31)

I am going to cut time and try to show Test Pack 1 data and Test Pack 2 data at the same time. Remember the one on the right is 50-percent DOD and the one on the left is 75-percent DOD. What we are looking at here is in mid season, end-of-discharge and end-of-charge voltages versus season number.

We have completed seven seasons on number one and eight seasons on number two. Right now the plan is to run this for ten seasons, and we hope that before the ten seasons are up, we will be able to get permission to continue it for twenty seasons, which would be simulating the 10-year life, which is the TDRSS requirement.

You can see that the end-of-discharge voltages are really flat. You are looking at possibly something less than 0.2 volt difference here, 27.8, 27.9. And over here we are looking at 28.8, 29.0.

End-of-charge voltages, we have a change here. We started here with a temperature compensated voltage limit when we were cutting off – I believe we started at 18.5 volts for the 12-cell pack, and we lowered it to 18. This adjustment here was lowered to 17.75 volts. I will explain why in probably the second vugraph after this, where you can see those pressures starting to increase on some of those cells.

I have adjusted the voltage here to be representative of our 24-cell battery rather than 12-cells.

(Figures 4-32 and 4-33)

We had a little problem with controlling the temperature when we started out. Actually, some of this is from some of the data – I think it was the noise. I am not sure that was a true data point, but it was there, so I had to put it down.

You can see our temperatures started and now leveled off to about 10.6 to 10.8°C. Here we got up to 11°C. Over here on Pack 2, we bounced around a little bit here. We had a problem with temperature control, but we are still about the same level, about 10 to 11°C. The ends of discharges are up to 17, 18, and 19°C, and over here they are running 20 to 22°C.

(Figures 4-34 and 4-35)

There are the cell pressure plots. Again it's all mid-season data, end-of-charge and end-of-discharge for mid season. We had a problem again at the beginning, getting the thing under control. But you can see it come down nicely. A P-1 and P-2. P-1 would be cell number, 6, P-2 cell number 12.

The circles are end-of-discharge pressure, and the squares are end-of-charge pressure. So these here would be the end-of-charge pressures, and these here would be the end-of-discharge pressures. You can see they are running nicely here.

Over here what is happening, the reason we had to do this voltage adjustment was that we were starting to get up a little bit high in pressure. It's really not high. We are looking at psia, so we are still looking at only a 2120, which is a little bit more than atmosphere. As soon as we made the adjustment, the pressure came right down and is looking very good.

(Figures 4-36 and 4-37)

The next ones we will be looking at are machine plots and are a little difficult to see, but they are the best we could do. The one on the right is a little bit better. The first scale over here is pack voltage, and the next one is pack temperature. This is cell pressure. These two are cell pressures and this is pack current.

This is for cycle 23, season six on both cases. This is pack voltage, and this line here is pack temperature. Up here we have the cell pressures, and that is the same in each case.

The reason again this is not a normal looking line here is that the current actually comes over here and then drops straight down as you would expect it would. Again, these are machine plots, and this is just the way the data came out when it was a product from the machine off the mag tapes.

(Figures 4-38 and 4-39)

We have chosen season six in both cases, again, 50-percent DOD there and 75-percent DOD over here. What we are looking at is the parameters for an entire season from 0 to 44 cycles: end-of-discharge voltage, end-of-charge voltage, recharge ratio, end-of-charge temperature, and end-of-discharge temperature.

Again, this is noise in the data. These are not true data points. Actually, our recharge ratio is running about 105, 106, in some cases, 104. Over here we are looking about 104, 105. Over on the end it looks about 106, 107.

(Figures 4-40 and 4-41)

We thought you would be interested in seeing what's happening when we reconditioned these 12-cell packs. They are reconditioned from a full state of charge, and they are reconditioned through the fixed resistors.

This is season number on the left. This is the capacity that we measured to 1 volt. This is the capacity we measured, residual capacity from 1 volt down to the cutoff voltage. This is the capacity that we put back in our recharge, and this is the end-of-recharge temperature.

Now, over under cell pressure, again P-1 is cell 6 and P-2 is cell 12. We have tabulated the cell pressure at the 1-volt point at the end of the residual capacity and then the cell pressure at the end of recharge.

You will notice on P-1 here, these are significantly higher than all the rest of them you see on either chart. The reason for this is that at the end of the first eclipse season on the discharge, we recharged the pack normally. At that time, we decided to do a worst-case kind of test on this current inrush, so we applied 20 amperes constant current for 10 minutes. As a result, the voltages got rather high, 1.6 volts, and we pumped the cell up.

I cannot explain why we got only high on one and not the other. But that is the reason these are so much higher than all the rest of them.

But you can also see a trend near the end. The pressures are starting to come down.

We have also made some measurements, and we did find that there was a significant amount of hydrogen in the cell. We think what is happening here is that our hydrogen is leaking slowly into the combinant. So things are looking very good.

(Figures 4-42 and 4-43)

The last vugraph is a summary of the reconditioning discharge cutoff voltages. On the bottom you will see pack voltages, 1.0, 1.7, and 1.1; and over here the same thing, 1.05, 1.01, 2, and so on.

If you look across, this is season 1, 2, 3, 4, 5 up to 7, and you can see they are staying – there is a little bit of a trend up here, but again we are looking at psia. So we are looking at practically zero volts, which is not much of a change.

We do have a couple in each pack. Here's two and here's a third one down here. But it is not getting down to 1/10 volt level. But they remain pretty constant. We have one over here. This is high. This one started out at 0.07 and it started to look as if it were working its way down. Now it is up to 0.95 volts again.

So far the cells are acting as we expected they would, and we expect they will last ten seasons, probably twenty seasons.

## DISCUSSION

BAER: I have two questions: The first question is, when you figure your percent return, that is right to the voltage cutoff. That doesn't include any trickle charge, does it?

KIPP: No, it does not.

BAER: The second question is, where were your temperatures measured?

KIPP: The temperatures are measured on the sides of the cells, on the narrow face halfway up.

THIERFELDER: You mentioned these cells had silver in the negative plates. Did the fleet Satcom have several negative plates?

KIPP: Yes, they do. By the way, one thought came to me in one question you asked on the previous paper, about whether the pressure or the temperature would get there first.

You notice we also have a temperature and emergency temperature cutoff in case the ground cover goes to sleep. We did do a check. We did make a test where we measured – we took a cell pack, we put on a heat exchanger plate, and we completely isolated it as best we could. We did run a test to determine which would get there first, temperature or pressure. Temperature won out. The pressure lagged the temperature significantly.

THIERFELDER: That's a function of the thermal system, so what you find would not necessarily be true on different thermal systems.

KIPP: That's true.

GASTON: You did mention that you are simulating the eclipse season, but not the sunlight season. Yet, you do want to do reconditioning, so there has to be some sunlight. How long is the sunlight period, or the simulated sunlight period?

KIPP: We did not simulate any solstice season at all. The end of the last cycle recharge period, we merely went into reconditioning discharge.

GASTON: But you do have each eclipse season?

KIPP: Absolutely.

HALPERT: That was an active cooling system you have?

KIPP: Yes.

HALPERT: What was the temperature of the cooling system, the cooling plate?

KIPP: I am sorry, I don't have the data for what the temperature of the cooling plate was.

HARKNESS: Ed, I have got one question on that one. When you reconditioned, you got over 50 ampere-hours out. When you put a resistor across the battery, did it take you about a week for the battery to run down?

KIPP: Yes. Actually, on the Pack 2, the 50-percent DOD, we had a 44-ohm resistor, which simulated one-half of what it would be for the full battery in the spacecraft. It takes about 8 to 9 days to get down. On the other one, it took about 4 or 5.

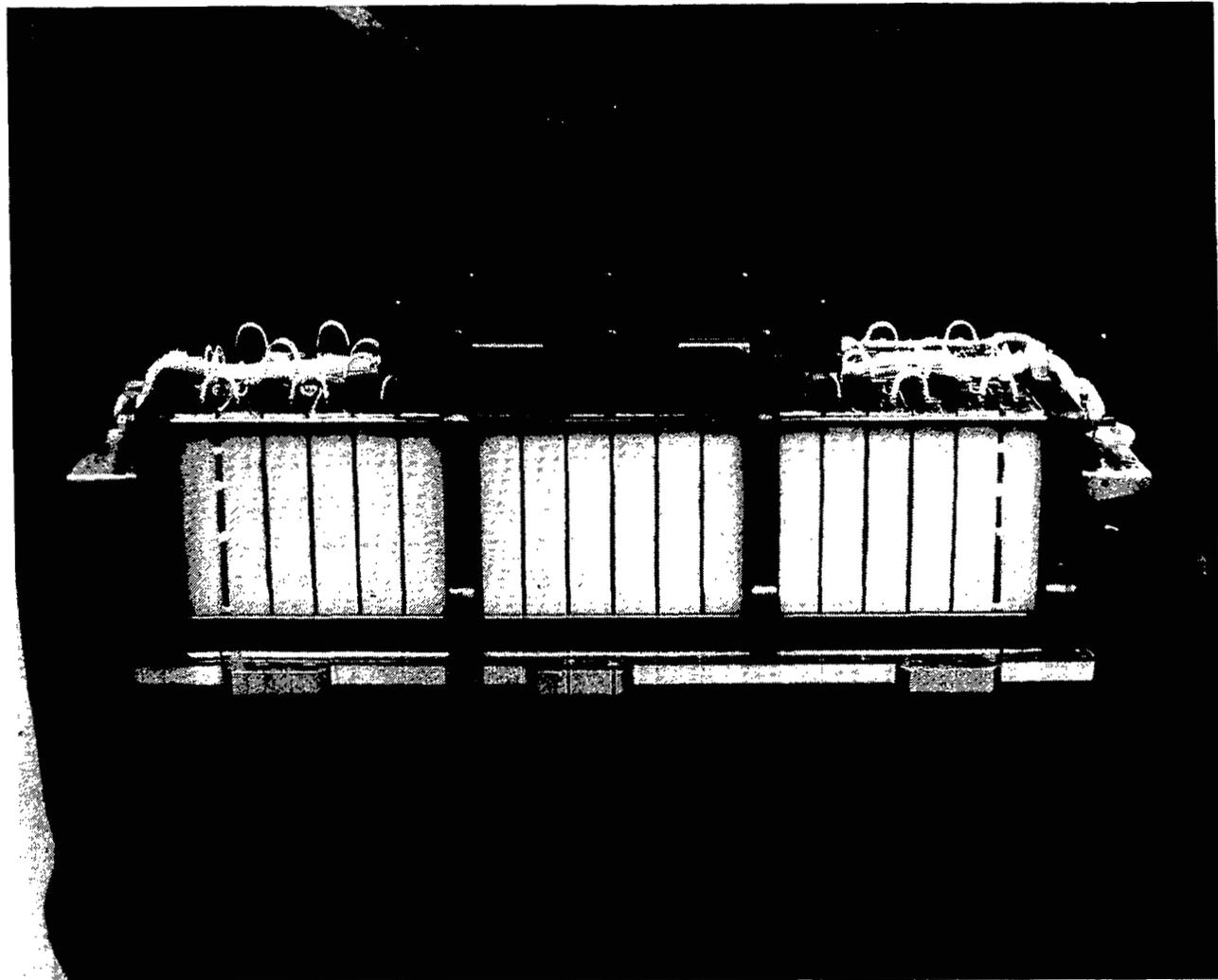


Figure 4-22

BATTERY DESCRIPTION

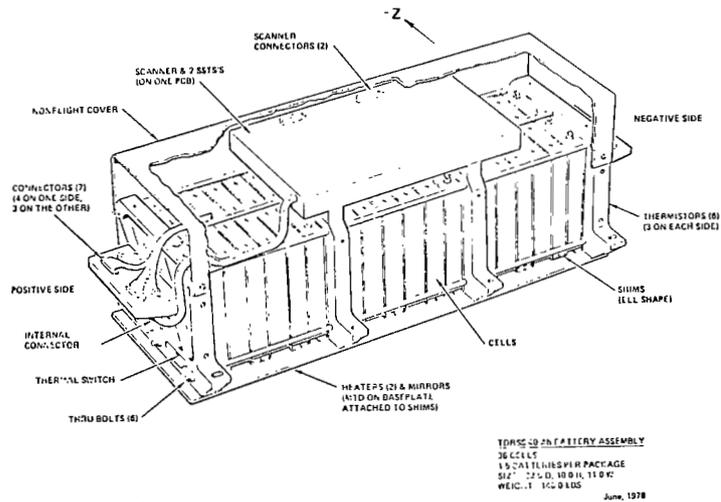


Figure 4-23

CELL DESCRIPTION

RATING: 40 AMPERE HOURS @ C/2 TO 1.0 VOLT @ 25°C  
 MINIMUM REQUIRED CAPACITY: 46.6 AMPERE HOURS  
 MANUFACTURER: GENERAL ELECTRIC  
 SIZE: HEIGHT 6.240" (6.62 OVER TERMINALS)  
 WIDTH - 3.404"  
 THICKNESS - 1.314"  
 WEIGHT: 3.25 LBS. (1482 GRAMS) MAXIMUM  
 CONTAINER: .019" THICK 304 L STAINLESS STEEL  
 TERMINALS: POSITIVE AND NEGATIVE INSULATED FROM CASE  
 ELECTROLYTE: 31.0 ± 0.5% KOH  
 PLATES:

	POSITIVE	NEGATIVE
QUANTITY	16	17
SIZE LENGTH	5.4"	-----
WIDTH	3.2"	-----
THICKNESS	.026"-.028"	.031"-.032"
SILVER TREATMENT	----	YES
TEFLON TREATMENT	----	NO

Figure 4-25

COMPONENT WEIGHT BREAKDOWN

CELLS (36)	114.48
END PLATES (2)	3.57
CENTER SUPPORTS (2)	2.04
THRU BOLTS (6)	2.16
THERMAL PLATE ASSY.	3.72
SHIMS	3.57
SPACER	.24
SCANNER	3.71
WIRE	1.20
POTTING & BONDING	.85
CONNECTORS	.55
MIRRORS	.38
MISC. (HARDWARE)	1.99
	<u>138.46</u>
TOLERANCE	<u>-2.00</u>
	140.46

Figure 4-24

BATTERY OPERATION - DISCHARGE

- BATTERY COMPLEMENT DISCHARGE CAPABILITY - 1440 WATTS FOR 1.2 HOURS.
- 3 BATTERY OPERATION - ~50 DOD.
- 2 BATTERY OPERATION - ~ LESS THAN 75% DOD.
- ORDNANCE LOADS ESTIMATED AT UP TO 50 AMPERES FOR 0.130 SECOND.
- BATTERIES ARE RECONDITIONED PRIOR TO EACH ECLIPSE SEASON.
- EACH RECONDITIONING DISCHARGE AT A ~C/100 THROUGH THREE PARALLEL RECONDITIONING CONTROL RESISTORS.

Figure 4-26

BATTERY OPERATION - RECHARGE

- BATTERY ON BUS ON RE-ENTRY TO SUNLIGHT. BUS VOLTAGE STABILIZED BELOW 40V.
- AFTER ARRAY WARMS, BATTERY COMMANDED OFF BUS AND ON TO FULL CHARGE SECTION OF ARRAY.
- BATTERY CHARGED AT CONSTANT CURRENT RATE TO A TEMPERATURE COMPENSATED VOLTAGE LIMIT.
- BATTERY COMMANDED OFF FULL CHARGE SECTION TO TRICKLE CHARGE SECTION OF THE ARRAY.
- TRICKLE CHARGE ADJUSTABLE BY SHUNTING RESISTORS.
- ON BOARD AUTOMATIC PROTECTIVE CONTROL SYSTEM IN EVENT OF LOSS OF GROUND SYSTEM.
  - AT 27°C AUTOMATIC SWITCH TO TRICKLE CHARGE.

Figure 4-27

(not available)

Figure 4-29

TEST PLAN

TEST TYPE	PACK 1 DEFINITION	PACK 2 DEFINITION
DISCHARGE - CONSTANT POWER	307 WATTS	240 WATTS
RECHARGE - CONSTANT CURRENT TO TCVL	0.14 AMPERES	0.07 AMPERES
TRICKLE CHARGE	0.14 AMPERES	0.07 AMPERES
TEMPERATURE - DISCHARGE	25-30°C	25-30°C
RECHARGE	7-10°C	5-10°C
TRICKLE CHARGE	2-10°C	0-20°C
INRUSH CURRENT - CYCLES 1 & 45 FIRST 10 MINUTES *OF EACH CHARGE CYCLES 21-25 PERIOD.	1/A	0.5 AMPERES
APPLICABLE TO PACK 2 ALL OTHERS ONLY TDRSS SIMULATION	1/A	1.0 AMPERES
RECONDITIONING - TO $\approx$ 1.0 VOLT PACK VOLTAGE BETWEEN ECLIPSE SEASONS	22 OHM LOAD	40 OHM LOAD

\*TCVL LIMITS DISABLED

Figure 4-28

MIDSEASON END OF DISCHARGE  
AND END OF CHARGE VOLTAGE  
VERSUS SEASON NUMBER

TDRSS LIFE CYCLE TEST  
PACK NUMBER 1  
75% DEPTH OF DISCHARGE

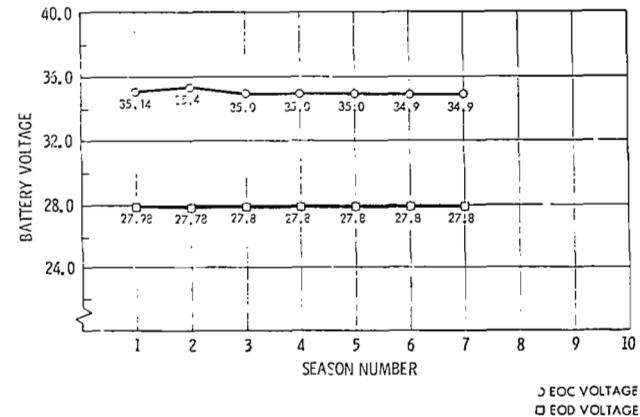


Figure 4-30

MIDSEASON END OF DISCHARGE  
AND END OF CHARGE VOLTAGE  
VERSUS SEASON NUMBER

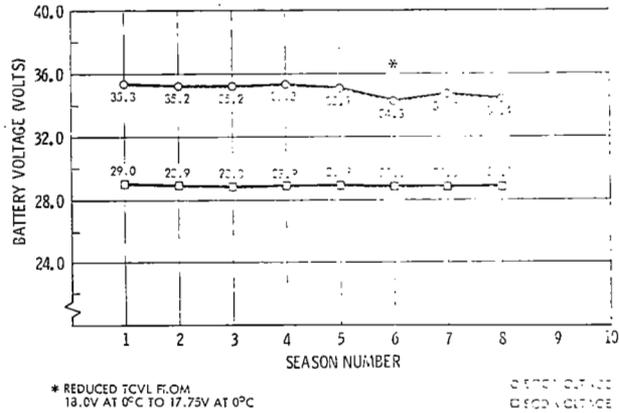


Figure 4-31

MIDSEASON END OF DISCHARGE  
AND END OF CHARGE PACK TEMPERATURE  
VERSUS SEASON NUMBER

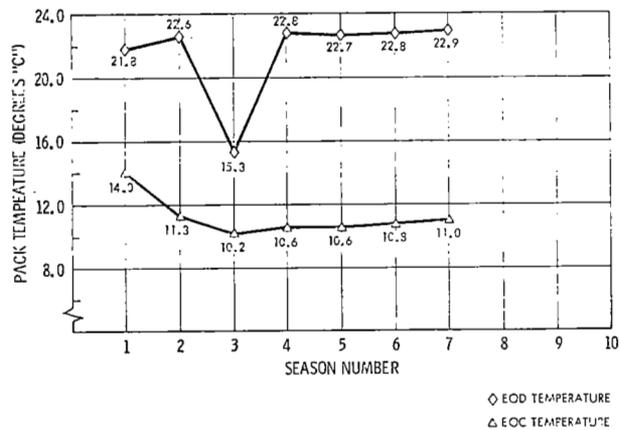


Figure 4-33

MIDSEASON END OF DISCHARGE AND  
END OF CHARGE PACK TEMPERATURE  
VERSUS SEASON NUMBER

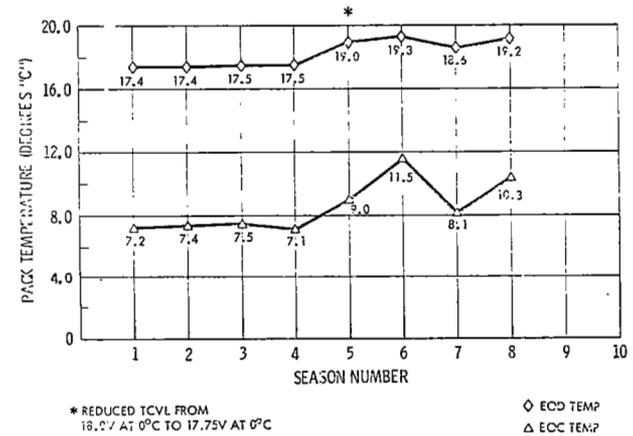


Figure 4-32

MIDSEASON END OF DISCHARGE  
AND END OF CHARGE PRESSURE  
VERSUS SEASON NUMBER

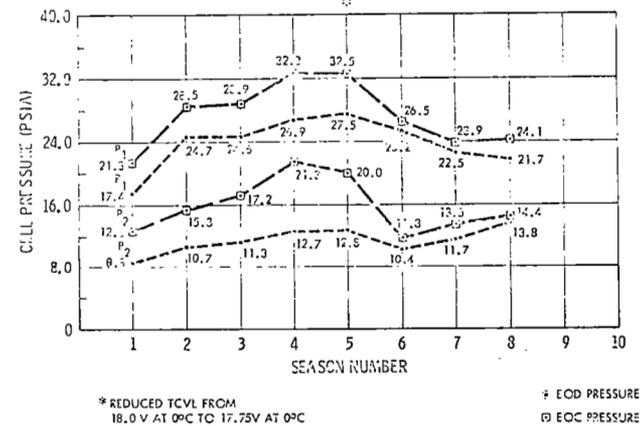
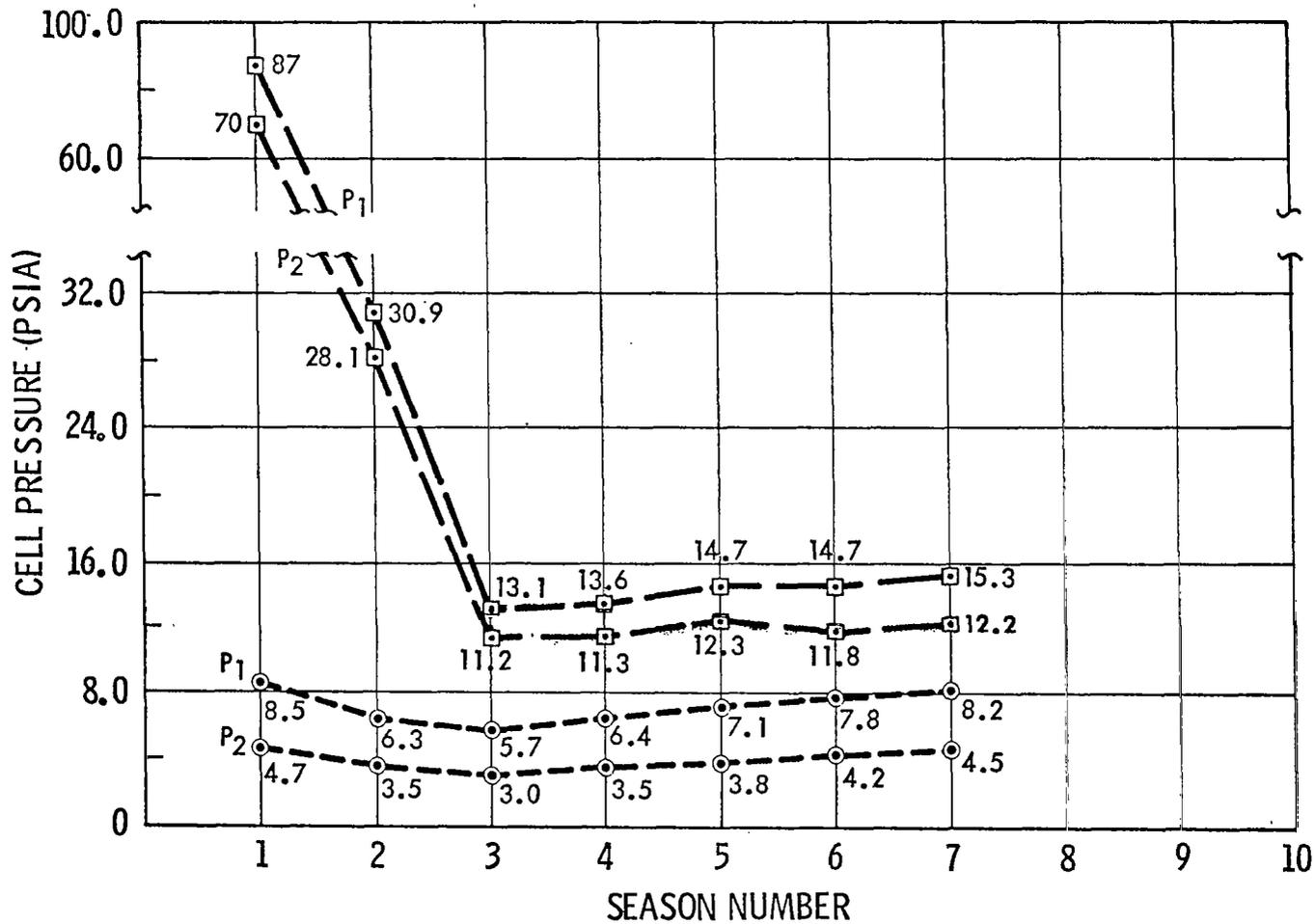


Figure 4-34

# MIDSEASON END OF DISCHARGE AND END OF CHARGE PRESSURE VERSUS SEASON NUMBER

TDRSS LIFE CYCLE TEST  
PACK NUMBER 1  
75% DEPTH OF DISCHARGE



318

Figure 4-35

⊙ EOD PRESSURE  
⊠ EOC PRESSURE

TEST PACK 2  
CYCLE 23 SEASON 6

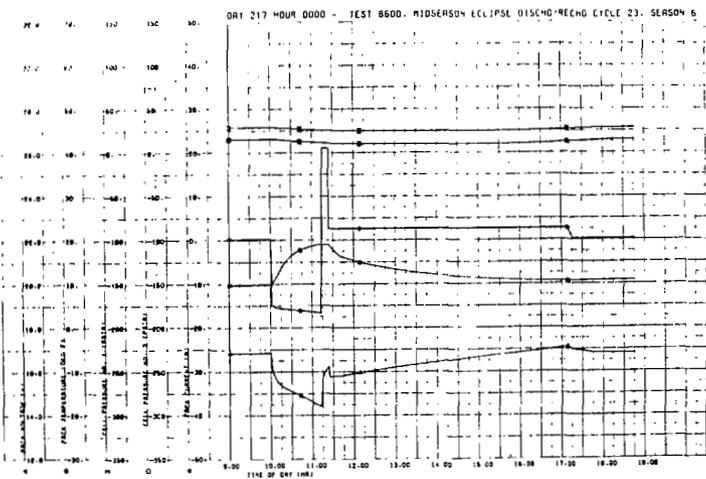


Figure 4-36

TEST PACK 1  
CYCLE 23 SEASON 6

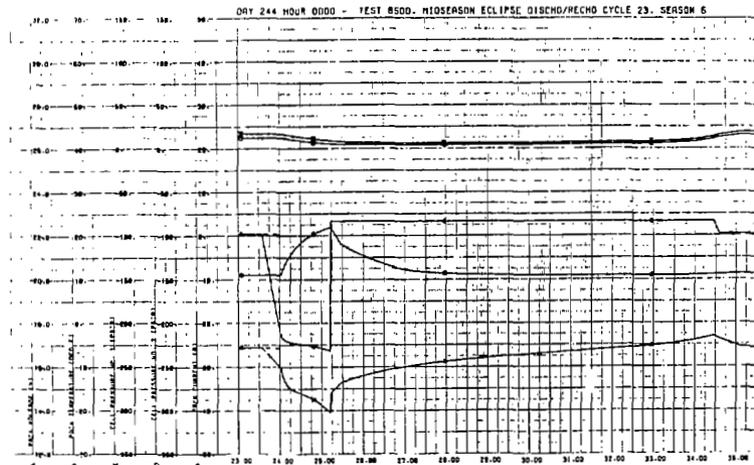


Figure 4-37

TEST PACK 1  
SEASON 6

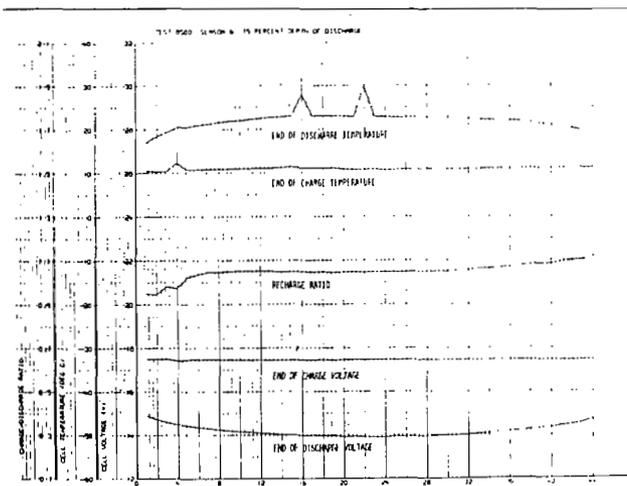


Figure 4-38

TEST PACK 2  
SEASON 6

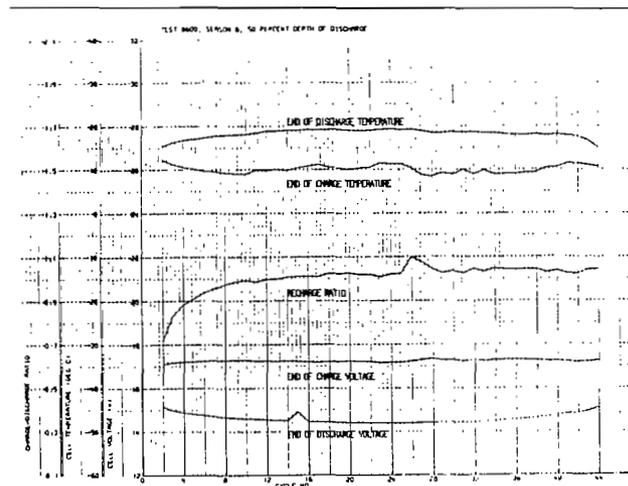


Figure 4-39

**RECONDITIONING  
DISCHARGE AND RECHARGE**

TDRSS LIFE CYCLE TEST  
PACK NUMBER 1  
75% DEPTH OF DISCHARGE

SEASON NO.	TO 1.OV	CAP RESI-DUAL	RECHG	END RECHG TEMP.	CELL PRESSURE (PSIA)					
					P <sub>1</sub>			P <sub>2</sub>		
					AT 1.OV	END RESI-DUAL	RECHG	AT 1.OV	END RESI-DUAL	RECHG
1	49.9	4.8	59.8	10.0	0.6	0.0	9.6	0.2	0.0	8.4
2	56.6	2.3	58.0	10.0	3.1	0.4	2.8	2.3	0.8	4.1
3	54.6	4.9	57.7	10.0	2.4	1.0	3.2	0.8	0.6	1.4
4	55.5	4.8	57.9	---	2.8	1.62	3.7	0.9	0.3	1.7
5	55.7	1.3	58.3	10.3	3.3	3.3	4.3	1.2	1.5	2.0
6	52.0	3.9	58.3	8.5	3.7	2.6	5.6	1.4	0.3	3.1
7	55.4	3.9	58.5	10.1	5.3	3.0	5.8	3.2	0.6	3.3

Figure 4-40

**RECONDITIONING  
DISCHARGE AND RECHARGE**

TDRSS LIFE CYCLE TEST  
PACK NUMBER 2  
50% DEPTH OF DISCHARGE

SEASON NO.	TO 1.OV	CAP. RESI-DUAL	RECHG	END RECHG TEMP.	CELL PRESSURE (PSIA)					
					P <sub>1</sub>			P <sub>2</sub>		
					AT 1.OV	END RESI-DUAL	RECHG	AT 1.OV	END RESI-DUAL	RECHG
1	52.8	3.62	57.3	6.3	17.3	40.5	35.8	6.8	7.0	9.9
2	53.3	3.89	59.1	6.6	16.7	32.0	41.7	6.4	5.3	13.6
3	52.0	4.38	58.2	6.4	16.7	50.4	50.3	6.4	4.9	7.1
4	53.2	3.75	56.0	9.6	16.7	39.0	39.5	8.0	5.7	6.1
5	55.5	4.76	57.8	7.8	17.1	43.2	41.8	8.2	5.6	7.3
6	55.3	2.89	56.3	7.4	14.3	26.6	23.1	6.9	5.9	7.1
7	54.8	3.77	60.5	17.6	15.6	31.1	31.6	8.6	7.6	17.0

Figure 4-41

**RECONDITIONING  
DISCHARGE CUTOFF VOLTAGES**

TDRSS LIFE CYCLE TEST  
PACK NUMBER 2  
50% DEPTH OF DISCHARGE

CELL NO.	1	2	3	4	5	6	7
1	-0.060	-0.071	-0.035	-0.068	-0.024	-0.090	-0.145
2	-0.060	-0.070	-0.041	-0.031	-0.021	-0.037	-0.134
3	-0.061	-0.070	-0.048	-0.054	-0.019	-0.030	-0.087
4	-0.058	-0.061	-0.067	-0.075	-0.103	-0.137	-0.152
5	-0.059	-0.070	-0.069	-0.074	-0.028	-0.099	-0.441
6	-0.058	+0.031	-0.066	-0.073	-0.081	-0.130	-0.153
7	-0.060	-0.071	-0.060	-0.073	-0.037	-0.078	0.138
8	-0.060	-0.072	-0.072	-0.079	-0.089	-0.131	0.464
9	+1.070	+0.975	+0.705	+0.933	+0.726	+0.994	0.955
10	+0.517	+0.645	+0.592	+0.639	+0.626	+0.449	0.582
11	-0.059	-0.072	-0.072	-0.077	-0.059	-0.127	-0.144
12	-0.058	+0.611	+0.344	+0.610	+0.105	+0.520	0.539
PACK VOLTAGE	1.00	1.73	1.13	1.55	1.00	-	1.47

Figure 4-42

**RECONDITIONING  
DISCHARGE CUTOFF VOLTAGES**

TDRSS LIFE CYCLE TEST  
PACK NUMBER 1  
75% DEPTH OF DISCHARGE

CELL NO.	1	2	3	4	5	6	7
1	-0.063	-0.069	-0.073	-0.116	-0.130	-0.150	-0.154
2	-0.067	-0.073	-0.079	-0.127	-0.146	-0.152	-0.156
3	-0.066	-0.072	-0.075	-0.100	-0.136	-0.148	-0.153
4	-0.055	-0.070	-0.074	-0.103	-0.137	-0.148	-0.153
5	+0.516	+0.558	+0.609	+0.595	+0.569	+0.585	+0.594
6	+0.509	+0.541	+0.354	-0.324	+0.476	+0.568	+0.582
7	-0.065	-0.070	-0.074	-0.052	-0.100	-0.149	-0.153
8	-0.060	-0.066	-0.020	-0.279	-0.382	-0.535	+0.595
9	-0.053	-0.068	-0.072	-0.106	-0.138	-0.149	-0.155
10	-0.067	-0.074	-0.077	-0.100	-0.139	-0.150	-0.155
11	-0.066	-0.073	-0.076	-0.123	-0.087	-0.150	-0.155
12	+0.598	+0.642	+0.650	+0.620	+0.592	+0.593	+0.608
PACK VOLTAGE	1.05	1.11	1.02	1.01	1.01	1.10	1.15

Figure 4-43

## LIFE TEST RESULTS OF THE NASA STANDARD 20 AMPERE HOUR CELLS

G. Halpert  
NASA/GSFC

NASA had a program to develop what is called Standard 20-ampere hour cells. We went to four manufacturers, General Electric, SAFT, Eagle Picher, and Yardney, to determine if there were some cells that could be used for competitive purposes in the future.

(Figure 4-44)

The manufacturers all delivered some 50 cells, 30 of which we sent to Crane for testing. Of the 30 which all were put through the initial evaluation tests that I described last year, 21 were placed in cell packs. There were four cell packs for near-Earth orbit and one cell pack for synchronous for each of the manufacturers.

My first chart here is a summary. You will recall that in the initial evaluation test, the GE cells all passed with flying colors. There were no problems at all. The SAFT cells experienced overpressure on the low-temperature tests. The Eagle Picher cells experienced overvoltage greater than 1.52 on several of the tests. And the Yardney cells had some kind of polarization and also had a variation in the characteristics. Nevertheless, we did select the better of these 30 to put into the four cell packs. The summary of where we are right now is the following:

We see the four manufacturers listed at the top. One pack from each manufacturer at 40-percent DOD and 10°C; one pack from each at 25-percent DOD and 20°C; one pack at 40-percent DOD and 20°C; and the fourth pack at 40-percent DOD and 30°C. All of these are near-Earth Tests.

Pack numbers, for your reference in the future, are associated with these various packs and begin with 12F for General Electric on the first, going down the column, 12F, then 12G, then 12H, and 12I. And back up to the top, SAFT would be 12J, K, L, and M. Eagle Picher would be O, P, Q, and R. N is left out for some reason. And Yardney would be S, T, U, and V. They are all "12" numbers, beginning with 12 and can be spotted in the Crane references.

As you can see where we are on the 10°C, 40-percent depth test, all the cells are continuing to work, giving reasonable voltages and capacities during this time period.

Every 6 months we do a capacity test on the pack. After the first 6 months, we take out cell 4 and perform a discharge on it – capacity test, that is. Next, at the end of 1 year, we do 3 and 4. At the end of 1 1/2 years, we do 2, 3 and 4; and at the end of 2 years, we do 1, 2, 3, and 4.

At the end of 2 years, we always have one cell that has never been discharged before during the 2-year period, whereas every 6 months we discharge the first cell.

In all conditions now for all four manufacturers under the two test regimes at 10 degrees and 40, and 20 degrees and 25 percent, we have had no failures.

The GE cells were removed at 40-percent DOD, 20°C tests on cycles run 11,000- 7 or 800, as you see there is 97. We had a significant deviation in voltages across the cell, and some cells were in overvoltage while others were not being charged. So we discontinued the tests at that time.

On the Eagle Picher cells we had a similar problem to what we had experienced in the early test. That is, they were running into overvoltage condition. When we cut back on the voltage, charged voltage level, we weren't getting the capacity. So we had to terminate that point.

They particularly showed up poorly on the 40°C – 40 percent, 30°C test. We see that we cut out very early for that very reason. That is, we were not getting capacity out, and when we raised the voltage level, we were running into high pressures.

The GE cells were deviating considerably from each other, some running high voltage and others running low. We ended up terminating it. You will see some of the voltage curves in a moment. The rest of the Yardney cells were all going. The SAFT cells were all going as of this point with those cycles.

(Figure 4-45)

Here is the capacity voltage test for cell number 4 only. In other words, every 6 months we discharged this cell in this particular pack which is a 20°C, 25-percent DOD.

You see several important points on this curve, as you will recognize, to be a consistent feature. That is, after you start going through this type of cycle which is charged to a given voltage level at a fixed current, and then taper, followed by a discharge at a constant rate, we see this second plateau, after we get over the 25-percent mark.

Here we have 25-percent DOD, and after that, we go to this very low plateau. If you will note, we are still above, in this case above 1.0 volts. So, on a battery level, we would still be above somewhere around 23 or 24 volts. So at this particular DOD, we are not in too bad a case.

We are running at a voltage level of 5, which is a 1.4, 1.5 volts per cell average, and the cells are pretty uniform.

The interesting thing on the table here is that the capacities are staying pretty well up there. Over the 2-year time period, the charge-to-discharge ratios are very low. It is going to be consistent with what you are hearing this morning and this afternoon about minimizing the C/D, and the end-of-charge current is staying rather constant. It is dropping a little bit, but staying rather constant.

Now, you might say you know cell 4 has been reconditioned every 6 months. What happens if you take one that's not reconditioned? So, I plotted the identical curve showing the first-time discharge for all four cells.

(Figure 4-46)

As you see, it is the same kind of thing that we are getting here, the same kind of results. I can almost overlap them, and you will see that there is hardly any difference between the two, which means the reconditioning really has not affected them very much. You will see some differences which are due to differences in individual cells.

There is one lower one here on the ones that have been discharged every 6 months. So, let's say that that had little effect.

(Figure 4-47)

Going now to the more severe cases, here we have the 20°C, 40-percent DOD. Again, you see the significant dropoff after we hit the approximately 40-percent mark, or right around the 40-percent mark. As you see, we already have failed here. Getting close to failure at this point is defined as a half volt across a given cell.

Again, the C/Ds are still fairly low for 40-percent DOD. This is CAP for capacity and has dropped off rather significantly over the time period. We did, at the very end, raise the voltage on this last one from 1.355 to 1.455 to see if we can get more capacity out. As you see, it didn't help very much.

(Figure 4-48)

These are all General Electric cells that we are still continuing to refer to here.

This is the last one of the four packs, 30°C, 40-percent DOD. We see rather a rapid dropoff within the first 6-month period, again, significant over the next 6-month period.

Again, we are getting out approximately 40 percent for quite a number of cycles, or close to the 40 percent before we drop off rather severely capacitywise. We do see a slightly small second plateau.

(Figure 4-49)

We don't have a lot of capacity data on the other cells because they haven't been operating that long. I did select the SAFT ones because we have three capacity discharges on it that have been completed.

This is a 10-degree, 40-percent DOD. You can see these are all at the level of 6; 1, 4, 5, 8 volts per cell at 10°C. You see again the second plateau, so that those who might say the second plateau

is only with GE cells, obviously we see it here, too, although they are slightly similar processes, fairly similar processes.

Again, we are still striving for that low C/D ratio, and the end-of-charge current is reasonable. I might add at 40-percent DOD. We charge at 16 amperes until the voltage cutoff, and then we discharge at 16 amperes until the 30 minutes is up.

At the 25-percent DOD, we charge at 100 amperes and then charge at 10 amperes until the voltage limit and then taper. On discharge we discharge at 10 amperes. So obviously we have different rates.

(Figure 4-50)

This is the 20°C, 25-percent DOD. As you see, we are seeing a rather significant second plateau after the 5 amperes.

(Figure 4-51)

Going up to 20 and 40 percent, there are similar kinds of things.

(Figure 4-52)

Finally, at the 30°C, 40-percent DOD, we have only completed the three capacity cycles there, and we are at about the 40-percent depth before we start failing at that point in time.

So the critical thing here is that although we are getting the capacity that we desire, we are a little concerned about the voltage, the second plateau, which means that under certain conditions, we might have to run a 22-cell battery at around 22 volts, which, I think, the electronics people would be very nervous about. It may be something we are going to have to look at in the future.

(Figure 4-53)

Now, with regard to the synchronous orbit cells, this is a summary table of the work that has been done to date on the synchronous cells.

Here we see the eclipse season, the seasons that we've had so far, and which, if we are looking down, the first one is running 16-percent DOD and 20°C here, we see here the first time we discharge cell 5, then 4, and 5, and then 3, 4 and 5, just as I indicated before, in sequence.

You notice, kind of interesting, that the capacities are staying up there rather well during that period of time, and they look pretty good even after six eclipse seasons of real-time operation.

Now, on the SAFT cells again, after three seasons, capacity is still holding up rather well. I have some data on GE, but I don't have the SAFT full data.

One interesting thing that really just came to light as I put this table together was that even though every one of these manufacturers produced cells that were supposed to be 24 plus or minus 2 ampere-hours, which was our requirement, in the initial testing that was done all of them came in almost exactly at 24. I would say at 24 plus or minus 1 ampere-hour. Very, very close.

But you will notice that even though the GE ones have been decreasing all the way down during this time period and the SAFT ones have been staying pretty close, look what is happening to the EP ones. They just increased. If that is correct, I don't understand it very well. But that is something strange.

On the Yardney ones, they have gone down in one case, in this lower cell. We indicated the Yardney cells had some kind of variation to it that weren't really very close.

(Figure 4-54)

Now, one on the voltage curve, I only have for the GE cell right now. You will notice that there is no second plateau on this curve on this particular orbit.

And the fifth orbit, I don't know if you can see the dots down here, I just hand-plotted them just before we went to press here. You can see they are coming down after the fifth orbit. They are still a little bit less than what they were before. At the 0.5 volt, they are still doing pretty well. But there is no second plateau in this type of orbit.

## DISCUSSION

GASTON: I have a question. When you say SAFT, do you mean SAFT America or SAFT France?

HALPERT: SAFT America cells built in this country.

GASTON: The second question on the geosynchronous cycling, is that a real-time or accelerated test?

HALPERT: Real time. Everything is real time.

GASTON: Did you recondition during sunlight?

HALPERT: No reconditioning, except if you consider every 6 months, we took the same cell down, then the next cell, and the next cell, and so on. No specific attempt to discharge a short in any particular time other than to measure the capacity.

GASTON: When you say "taking them down," do you take in major eclipse time on a specific cell?

HALPERT: Yes, a specific cell. Two for the next 6 months, 3 for the next, and so on.

HENNIGAN: I was wondering how you keep the temperature constant on these cells?

HALPERT: The cells are in a temperature cabinet in which the air is blown. And there are fins between the cells but not mounted to any baseplate.

HENNIGAN: The other question is, did you compare these GE cells with the 6 ampere-hour cells that are running for quite a while now?

HALPERT: You mean the accelerated test cells?

HENNIGAN: Well, what we call the normal cells, the control cells.

HALPERT: I have not had a chance to relate these to those.

NASA STANDARD CELL  
NEAR EARTH ORBIT TEST  
AT  
NWSC CRANE

TEST REGIME: 40% DOD, 10° C

CYCLES

<u>CELL</u>	<u>GE</u>	<u>SAFT</u>	<u>EP</u>	<u>YD</u>
1 to 4	12710	6953	6173	5180

TEST REGIME: 25% DOD, 20° C

<u>CELL</u>	<u>GE</u>	<u>SAFT</u>	<u>EP</u>	<u>YD</u>
1 to 4	12851	7131	6159	5375

TEST REGIME: 40% DOD, 20° C

<u>CELL</u>	<u>GE</u>	<u>SAFT</u>	<u>EP</u>	<u>YD</u>
1	11703-F		4570-F	
2	11897-D	7006	4080-F	5457
3	11794-F	(all cells)	4523-F	(all cells)
4	11794-F		4687-F	

TEST REGIME: 40% DOD, 30° C

<u>CELL</u>	<u>GE</u>	<u>SAFT</u>	<u>EP</u>	<u>YD</u>
1	9266-F		677-D	
2	8124-F	7042	679-D	5361
3	9012-F	(all cells)	679-D	(all cells)
4	8933-F		626-F	

F - Failed  
D - Discontinued

NOTE: Test status as of 9 November 1979

Figure 4-44

NASA STANDARD 20AH CELL  
NWSC/CRANE PACK 12G — GE CELLS  
20°C 25% DOD

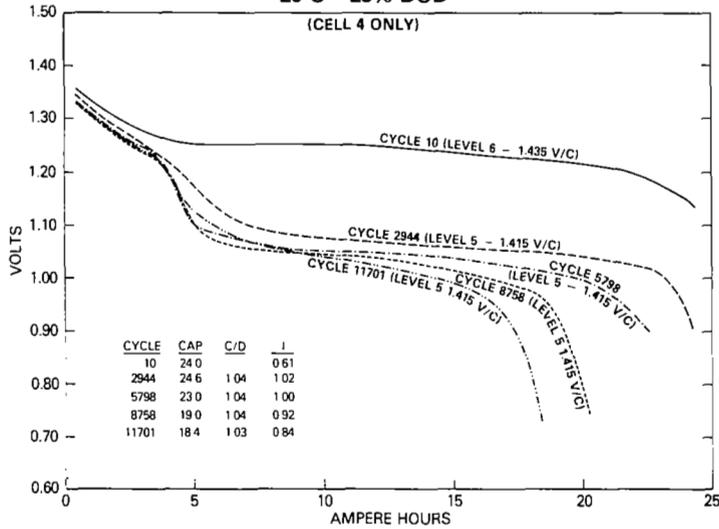


Figure 4-45

NASA STANDARD 20AH CELL  
NWSC/CRANE PACK 12G — GE CELLS  
20°C 25% DOD

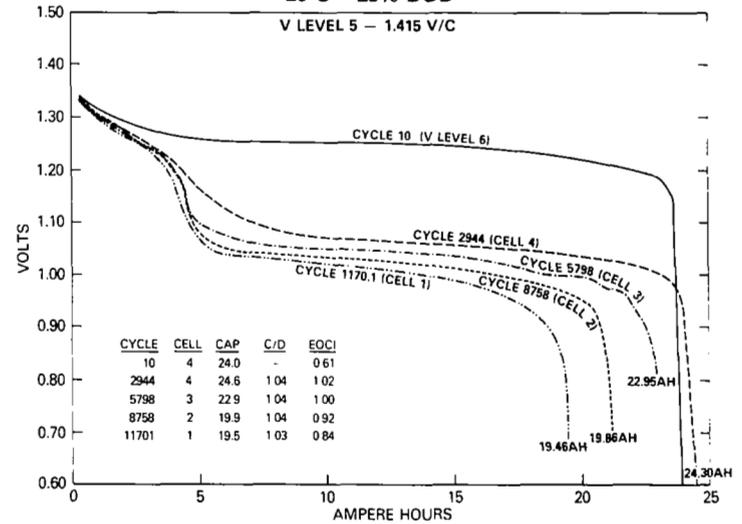


Figure 4-46

NASA STANDARD 20AH CELL  
NWSC/CRANE PACK 12H — GE CELLS  
20°C 40% DOD

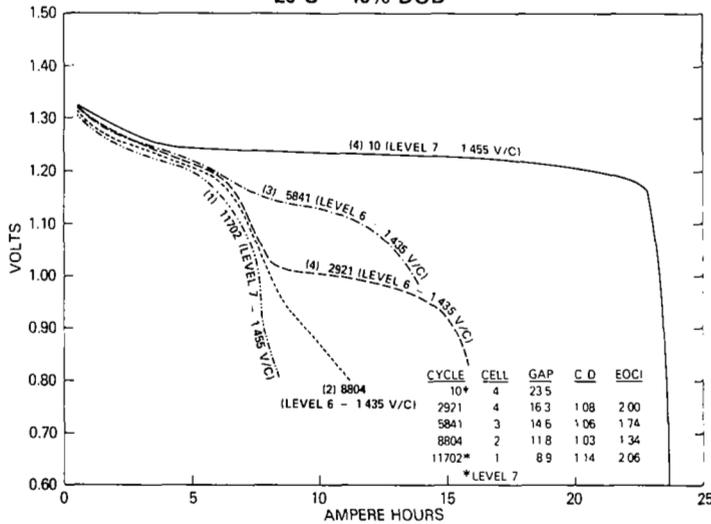


Figure 4-47

NASA STANDARD 20AH CELL  
NWSC/CRANE PACK 121 — GE CELLS  
30°C 40% DOD

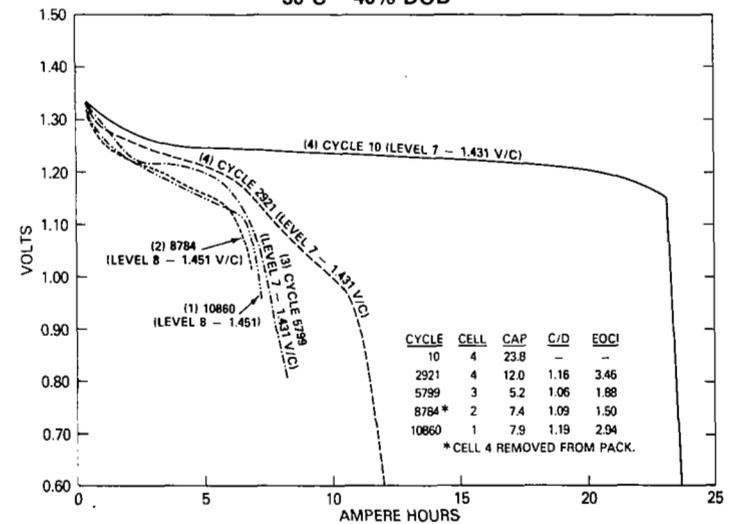


Figure 4-48

NASA STANDARD 20AH CELL  
NWSC/CRANE PACK 12J – SAFT CELLS  
10°C 40% DOD

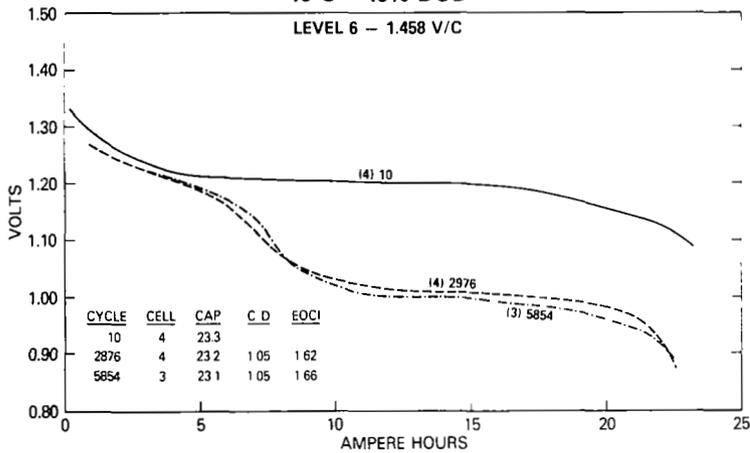


Figure 4-49

NASA STANDARD 20AH CELL  
NWSC/CRANE PACK 12K – SAFT CELLS  
20°C 25% DOD

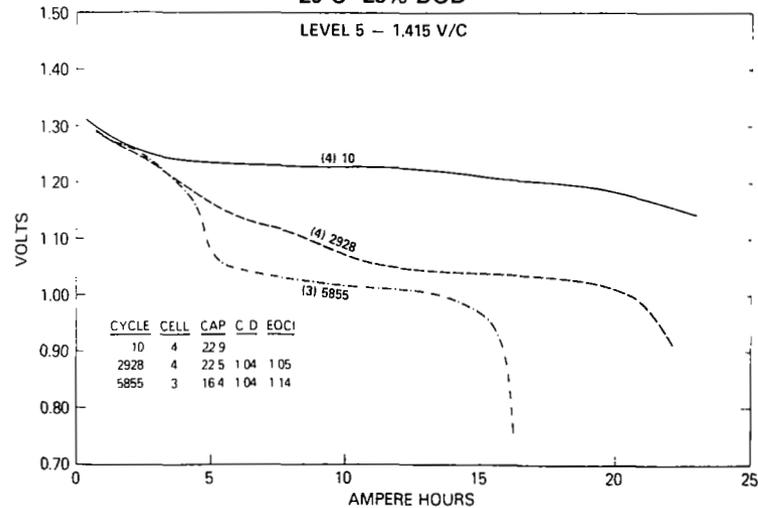


Figure 4-50

NASA STANDARD 20AH CELL  
NWSC/CRANE PACK 12L – SAFT CELLS  
20°C 40% DOD

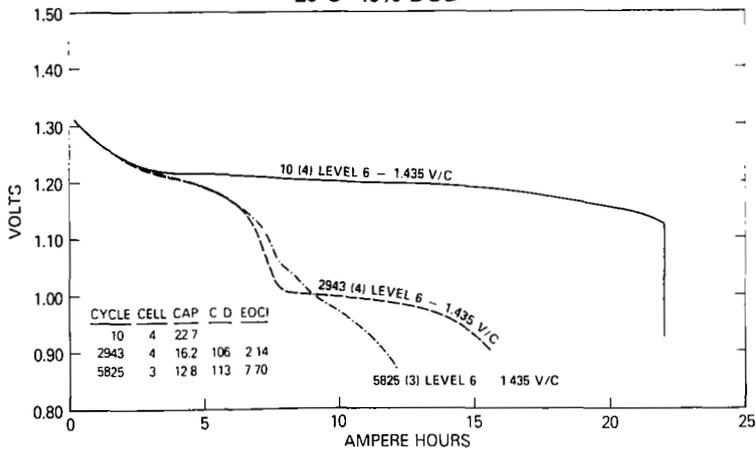


Figure 4-51

NASA STANDARD 20AH CELL  
NWSC/CRANE PACK 12M – SAFT CELLS  
30°C 40% DOD

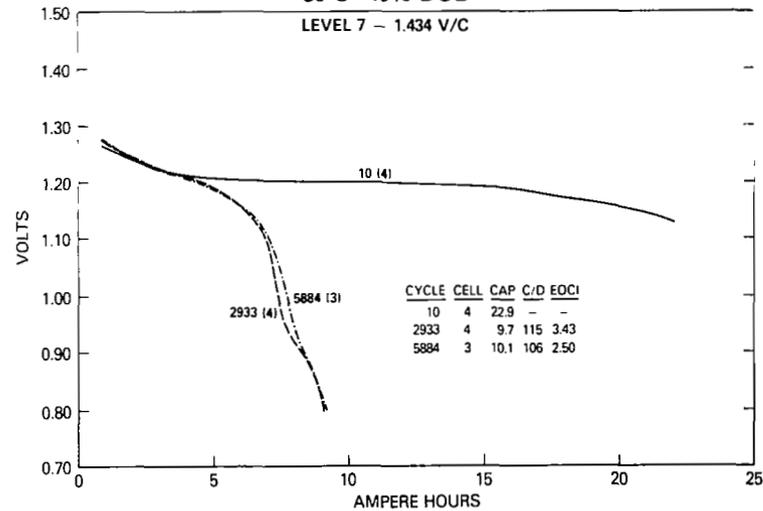


Figure 4-52

NASA STANDARD CELL  
 SYNCHRONOUS ORBIT TESTS  
 AT  
 NWSC CRANE

TEST REGIME: 60% DOD, 20° C

CAPACITY TESTS

AMPERE-HOURS OUT

<u>ECLIPSE</u>	<u>CELL</u>	<u>GE</u>				<u>SAFT</u>			<u>EP</u>			<u>YD</u>		
1	5					24.6		23.6		26.1			24.1	
2	4,5			24.1	22.5		23.7	23.3	28.0	27.6		21.9	24.1	
3	3,4,5	22.6	21.9	21.4		23.7	23.5	23.2	28.6	28.0	28.0	23.8	21.5	24.4
4	2,3,4,5	22.0	20.9	20.4	20.9									
5	1,2,3,4,5	21.7	20.7	20.7	20.1	20.7								
6	5					21.0								

Figure 4-53

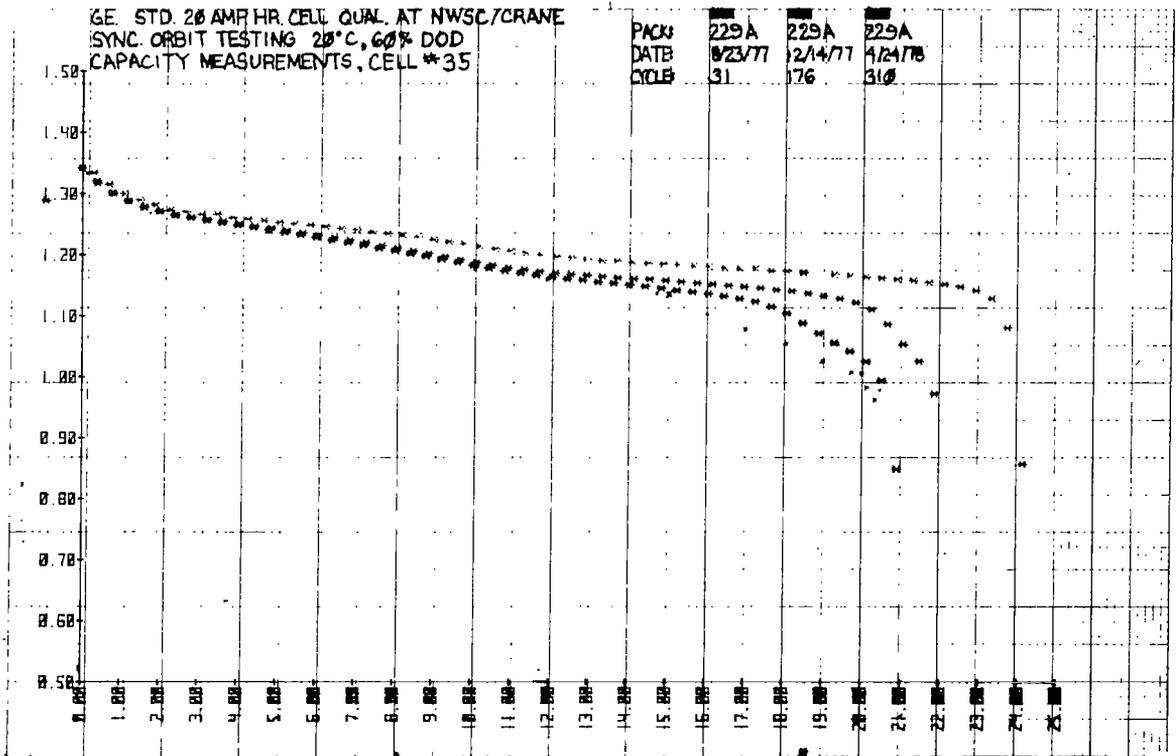


Figure 4-54

## BATTERY RECONDITIONING, SUMMARY OF TRW EXPERIENCE

W. Scott  
TRW

I would like to present a summary of data that relates to the results of reconditioning that we have accumulated from three different spacecraft programs at TRW. I hope that most of this data will be new to you so that it will be of considerable interest.

I think it will add significantly to the engineering data base for reconditioning and hopefully increase the level of credibility of this process for general use.

(Figure 4-55)

First, I would like to show the basic design characteristics of the three programs that I am going to talk about.

First, all three are 24-hour synchronous orbit applications: Program A, 24 ampere-hour cells, GE, 22 cells in series. Program B, 12 ampere-hours, Gulton cells, manufactured approximately 1970, 1971, 22 in series. The third, fleet Satcom program which you have heard about, 24-ampere hour cells, GE, 24 cells in series. Each of these spacecraft has three batteries operating parallel, more or less, directly connected to the bus. The first two operating approximately over the same temperature range, 60 to 80 to 85°F. The fleet Satcom operates at a significantly lower temperature range. Also, the first two are operating at a designed maximum DOD 35 to 40 percent. Fleet Satcom is a designed maximum of 75.

As to reconditioning parameters, I showed two different reconditioning load resistors from the programs A and B because until recently the batteries had 44-ohm resistors used for reconditioning discharge.

Recently we have started to install higher load resistances, as indicated by B under each of those two. Fleet Satcom has about an 85-ohm resistance across 24 cells.

There is also a difference in the end voltage used to terminate the reconditioning discharge. These numbers you see here are the numbers presently used in flight. There is some difference right now in the way in which some of these programs are being tested on the ground and the way they are being actually operated in flight.

As you see here, the minimum voltage per cell that we are using is with the fleet Satcom program, which in flight has the highest resistance per cell. The 44 ohms for the programs A and B apply to the spacecraft, to the older spacecraft in flight, and they are going down to 0.9 and 1 volt per cell respectively.

(Figure 4-56)

I am going to show both ground test and flight data for two out of the three programs. I am going to show ground test data only for program A because it was just too much of a hassle to get the right kind of comparable flight data for program A. But we have quite a bit of ground test information.

This is the 24-ampere-hour GE cell discharged for reconditioning purposes into the 44-ohm resistor to approximately 1 volt per cell, 0.9 to 1 volt per cell.

What I have shown here is the data for actually three life tests conducted over a period of several years in connection with a long-term storage effects test that was completed a year or so ago. Battery serial number 13 was tested after 4 years of ground storage; battery 15 after 5 years; and 15X after 6 years.

On the first line I show the capacities actually taken out during the reconditioning discharge to 20 volts, which is about 0.9 volt per cell. You can see they are all roughly about the same and fall within a rather narrow range. What you are actually seeing there is the range for a 10-eclipse season test where we actually did a reconditioning discharge between each eclipse season.

Actually, that means that there were nine such discharges done during each of these life tests, and that is the range we obtained for all nine such discharges in each of those life tests. And you can see that the range is quite narrow.

To compare with that, the next line shows the range of end of discharge, minimum seen during each eclipse season, at the middle of the eclipse season, after 1.2-hours discharge.

Here again the range is very narrow. There was very little trend if any. If you look at the whole curve, you see a slight drop after the first eclipse season, but no significant change after that. I didn't plot any of these because the plots are rather dull. It looks like a flat, straight line, which isn't too interesting.

Some full load capacity data is at the bottom. All this testing was done using constant power loads for load discharge, and the capacity measurements were also measured on the constant power load, which were 300 watts for the 22-cell battery. Capacities to 25.5 volts of the battery were shown before each life test, 29.4, 28.7, and 27.9.

After the completion of each life test and a final reconditioning cycle, you can see that the capacities are a little bit less where we measured them on batteries 13 and 15. For some reason or other, it didn't get measured on the last one.

Now, in the middle of the final life test on serial number 15X, we did a power discharge after completion of season number 6 and before we did the reconditioning. We got 20 ampere-hours.

Then, we did the reconditioning and then did another 300-watt constant power discharge, and we got 25.4. So this indicates the mid-test response to reconditioning that we have attained.

(Figure 4-57)

For program B, we have both ground test and actual flight data. Although in this case, that data are not on the same type of cell, unfortunately.

You may have noted on the first graph that earlier spacecraft were made with Gulton cells. The more recent ones are being made with General Electric cells.

This data I have here for ground testing is for General Electric cells, and it shows the results over five eclipse seasons of accelerated testing on the ground with two different sizes of reconditioning resistors.

Again, I have left the data in the form of digital data so that it makes it easy to compare numerically with other data that you might have available.

I want to point out that again, after a slight adjustment during the very beginning of the test, there appears to be no trend either upward or downward in the end of discharge, minimum end-of-discharge capacity during mid season throughout the tests to date. Now, in addition to that, we have some of the actual reconditioning capacity data such as I showed on the previous graph.

For the 44-ohm resistance case, we take the battery to 19 volts. And the only data I could come up with was 14.5 ampere-hours. These are 12-ampere-hour rated cells, we call them for this program.

For the discharge into 167 ohms, we go down to 12 volts in this case for this ground test. We started out at 19 ampere-hours. There has been a small change down here, but it is hanging right in there.

(Figure 4-58)

This is flight data for two spacecraft of the B program. These are data for Gulton cells. These cells, as I indicated, were made around 1970, using SAFT plate material.

Again, we are getting very constant results after the first eclipse season. But notice also that we show what kind of a program of reconditioning we are carrying out in this particular case.

We had no reconditioning for the first two eclipse seasons, one cycle after the next one, and two cycles from there on for flight B2. Flight B1 had some operational problems after the sixth eclipse season, and the data is not comparable.

Incidentally, the reason we are doing two cycles on this spacecraft is that we found with the 44-ohm resistor the first discharge curve sometimes looks rather limp after an eclipse season, particularly after 3 or 4 eclipse seasons have passed. But the second one looks much better, and we get considerably more capacity out. So we have sort of got in the habit of doing two reconditioning cycles when we use the lower resistor for discharge.

(Figure 4-59)

The third program is fleet Satcom. Now I don't want to bore you with old data, but I want to show you the final outcome of the fleet Satcom cell pack life test. I don't believe some of you have seen the data right up to the very end of the test. Ed said that this test had gone for 42 seasons. As a matter of fact, it went for 44.

(Figure 4-60)

There are the results in terms of end of discharge voltage. This stuff down here has been reported on earlier. I think the last report on this program carried the data out into here somewhere. Now, this carries the data out to the last eclipse season that was performed on this test before it was terminated.

I will talk a little bit about this part of the behavior in just a moment. But as you may recall, a different method of reconditioning discharge was used from here on in which a very low rate was used to take the battery down to a very low battery voltage.

During this part, the battery indicated by the triangles was discharged at a full load rate down to 1 volt, and then down to 1 volt again on a 25-ohm resistor for 12-cell pack. And the battery looked pretty bad after approximately 12 eclipse seasons with that type of reconditioning. So that was why we went over to the much lower rate with the results that you see here.

(Figure 4-61)

Now, again, this is not particularly new data, but I do want to emphasize that we have a record of the capacity withdrawn on these reconditioning discharges as the test proceeds. In this case up to season 30 where the capacity more or less leveled off and remained constant for the rest of the tests.

You can see that during that period of the test where the end-of-discharge voltage during regular eclipse season declined rapidly, we also got a rapid decline in the available capacity on reconditioning discharge.

Incidentally, all the capacities are measured to 1 volt per cell, even though the reconditioning discharge was taken down to a lower voltage than that.

After we reduced the rate and began taking the battery down to a lower voltage, the capacities recovered to essentially where they were when the cell was new, and it remained there throughout the rest of the test.

(Figure 4-62)

This is flight data for fleet Satcom, which I don't believe many of you have seen yet. For the one flight that has completed four eclipse seasons to date, this data shows that we did not

recondition prior to the first season, but have done one cycle of discharging on 85 ohms to approximately 3/4 volt per cell prior to each season after the first.

The capacities obtained on this reconditioning discharge for the three batteries on the spacecraft are indicated here. They are very, very even.

Minimal voltage during the season is battery voltage, range of the three batteries. I didn't even bother to calculate the difference between maximum and minimum to within the accuracy allowed by the telemetry system. There has been no change whatsoever in the minimum end of discharge voltage seen on this spacecraft to date.

In summary, what we are seeing is that the effects of reconditioning, when they are beneficial, are correlated best, of all the different variables that we looked at, and are correlated best with the capacity that we obtained during the reconditioning discharge. In this case, usually measured to 1 volt per cell.

You can discharge at a higher rate, you can discharge at a lower rate, and you can discharge to various end voltages. But as long as you get some minimum capacity out – and we don't know exactly what that minimum is, but, in all cases, it was something of the order of 10 percent greater than the rated capacity of the cell – as long as you can maintain that lowest capacity numbers, you can expect that you can get good results from your reconditioning discharge.

So we submit that possibly that capacity might be a more basic criterion to use to judge when you have completed reconditioning than the other variables you might think about.

## DISCUSSION

LEAR: Dr. Scott, on your B test, you said that you did two cycles; the first cycle was bumpy – and it's a two-part question – did you have individual cell control on that?

SCOTT: You mean individual cell voltage monitoring? No. That data that I referred to is flight data.

LEAR: Then you might attribute the bumps to be the cells reversing as you got down close to the . . . .

SCOTT: That's a good question. It's always difficult to interpret bumps on discharge curves in flight without individual cell data. It's a judgment call.

We believe that if the rate of change of voltage with time or with capacity is less than a certain number, then it probably isn't a cell reversal. It's usually a transition between plateaus or other things.

Usually, by looking, comparing that flight, some of that flight data with some of the things we have seen during ground tests where we have occasionally got cell reversals during discharge, we

see a much sharper dropoff in voltage. A sharp dropoff in voltage is necessary to indicate a cell that might be reversing. I won't say that we have never seen that in flight, but we have not seen it on any of the examples I am giving here, any of these programs.

NAPOLI: Dr. Scott, on that one chart that you showed where you had the fleet Satcom craft test, at one point you changed the reconditioning discharge rate. Is that when you went down to lower levels than 1 volt per pack?

SCOTT: Right. We changed the rate and simultaneously allowed the pack to go down to something around 1 volt at the pack level.

NAPOLI: At the pack level. So basically you brought the cells down to zero?

SCOTT: Well, there were cells reversed during most of those discharges.

Yes, in the past, I believe we have indicated the kind of reversal behavior in general that we have seen and indicated that we have not seen any significant increase in pressure in those cells and that there is no sign of any problems throughout that test.

As a matter of fact, I recently looked at that data again and found that after the second or third such low discharge, that we had reversed 8 of the 12 cells in the pack every single time that we did that discharge. So that must have occurred for at least 30 different times before that test was terminated with no ill effects at all.

NAPOLI: Are you making any conclusion or recommendation on your opinion, or TRW's opinion of reconditioning, how beneficial is it, and down to what level would you recommend doing it on an operational satellite?

SCOTT: Well, I don't know that we are ready to make an official recommendation. But, unofficially, from an operational standpoint, we believe that the lower the discharge rate the better, because if it is low enough, you don't have to worry if you might reverse a few cells.

The operational problems of operating a battery under those conditions in orbit are much less than those if you are discharging at a higher rate where you have to worry about reversing cells.

So in addition, as the cells age, it appears that the amount of capacity that you can take out to any end voltage, decreases at any given rate. So that the lower the rate you start out with, the better chance you have of maximizing the output on a reconditioning discharge and therefore obtaining the maximum benefits. But exactly what voltage you have to go to, I don't think is the key factor right now. I think if you can get out some minimum number which is not yet really defined, some minimum fraction of the real capacity in the cell, you have done the job.

HENDEE: Perhaps you mentioned and I missed it, but if you had 44 seasons on your test, this is obviously an accelerated test?

SCOTT: That's correct.

HENDEE: That was on test C. Were A and B also accelerated?

SCOTT: Yes. The ground life tests that I have shown are all accelerated to the extent that the maximum between eclipse seasons time is of the order of 2 weeks.

HENDEE: That covers your reconditioning time plus a bit.

SCOTT: Right.

GASTON: One of your earlier slides showed that the ten eclipse seasons were conducted after 4, 5, and 6 years of ground storage.

Ground storage, first of all, I assume that is in a shorted state, cold temperature that the cell was kept at that condition. Second of all, I conclude from that that the cell performs perfectly well if kept up to 6 years in cold storage.

In other words, is the cell still flightworthy?

SCOTT: In this case, I would agree that the best known way of storing batteries is discharge shorted and at some low temperature. However, it is interesting that the three batteries that we put through this storage test were out of storage and at room temperature for significant periods of time.

So they do not represent, necessarily, a continuous period of low-temperature storage. Some of them were out doing other things for probably as much as half of their total storage time. But they were shorted essentially all that time.

GASTON: And yet their performance appears almost identical.

SCOTT: That's right.

One of several things that I believe is, of course, that the effect of proper reconditioning will overcome many of the problems associated with storage and improper handling that people have had in the past. I am convinced of that. That may have been what we were really doing here. I am not sure.

The other thing is that these were operated at a relatively mild depth of discharge, and I don't think that was particularly a severe type of test. The fleet Satcom test being at 70, 75 percent was considerably a more severe test.

HARKNESS: One more question. Joe?

LACKNER: I would like to make a comment on some of your findings. You note particularly after the reconditioning season, you went from 28 ampere-hours to 20 ampere-hours. After reconditioning you went back up to 25 ampere-hours.

Well, what we found on the CTS satellite, which is now in its fourth year of operation, as we go into the eclipse season for the first half of it, where we are actually increasing the ampere-hours out, we do get a recondition effect. In fact, it does improve.

It is during the second half of the eclipse season that there tends to be a slump. I think several people in their curves have noted that. So this past eclipse season we decided that what we would do is try to have a maximum load and increase the load throughout the eclipse season.

When we hit our peak eclipse day, instead of having a decreasing ampere-hour load, we had it on a ramp function and continued to increase the ampere-hour load out of it. What we found was that we didn't get a slump in the second half of the eclipse season, but it stayed relatively steady. And at the end of the eclipse season, we didn't get that dropoff that you noted.

So this may be a bit of a compromise for people who are sitting on the fence about reconditioning and nonreconditioning and need something on an operational basis.

TRW SPACECRAFT BATTERY DESIGN SUMMARY

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PROGRAM DESIGNATION	ORBIT	CELL CAP. AH. RATED	CELL MFR.	NO. OF IN SERIES	NO. OF BATTERIES PER S/C	OPER. TEMP (°F)	NORMAL	RECONDITIONING PARAMETERS	
							MAX. DOD (% OF RATED)	DISCHARGE LOAD RES. (Ω)	NORMAL DISCHARGE END VOLTAGE(V)
A	24H SYNCH.	24	G.E.	22	3	60-80	40	A) 44 B) 150	20(0.9V/CELL) --
B	24H SYNCH.	12	GULTON (F, 3 & 4) G.E. SUBSEQ.	22	3	60-85	35	A) 44 B) 167	22(1.0V/CELL) --
FLEETSATCOM	24H SYNCH.	24	G.E.	24	3	40-60	75	85	18(0.75V/CELL)

Figure 4-55

TEST DESCRIPTION: SIMULATED ORBITAL LIFE TEST - FLIGHT CONFIG. BATTERIES  
DOD 55% OF RATED CAPACITY (13AH/24AH CELL)  
10 ECLIPSE SEASONS - ACCELERATED SCHEDULE  
PRIOR HISTORY - 4, 5 AND 6 YEARS OF GROUND STORAGE

	TEST BATTERY SERIAL NUMBER		
	S/N 13 (4 YRS.)	S/N 15 (5 YRS.)	S/N 15X (6 YRS.)
CAPACITY ON RECONDITIONING DISCHARGE (AH TO 20 V) (44 OHMS)	31.25-31.50	31.00-31.82	31.90-32.60
RANGE OF MINIMUM EOD VOLTAGE DURING LIFE TEST (10 SEASONS)	26.1-26.2 (1.190V/CELL)	26.2-26.6	26.2-26.5
FULL LOAD (300W) CAPACITY (AH TO 25.5V)			
BEFORE TEST	29.4	28.7	27.9
AFTER TEST	27.9	27.6	NOT MEASURED
AFTER SEASON 6 AND:			
BEFORE RECOND.	-----	-----	20.00
AFTER RECOND.			25.4

Figure 4-56

ECLIPSE SEASON NO.	RECOND. PRIOR TO SEASON	MINIMUM VOLTAGE DURING SEASON			
		FLIGHT B1 *		FLIGHT B2	
		BATTERY	V/CELL	BATTERY	V/CELL
1	NONE	26.7	1.214	26.7	1.214
2	NONE	26.4	1.200	26.1	1.184
3	ONE CYCLE	26.5	1.206	26.2	1.189
4	TWO CYCLES	26.5	1.206	26.3	1.195
5	TWO CYCLES	26.4	1.198	26.3	1.190
6	TWO CYCLES	26.4	1.200	26.2	1.190
7	TWO CYCLES <sup>(1)</sup>	NA	NA	26.2	1.190
8	TWO CYCLES <sup>(1)</sup>	NA	NA	26.2	1.190
9	TWO CYCLES <sup>(1)</sup>	NA	NA	26.2	1.190
10	TWO CYCLES <sup>(1)</sup>	NA	NA	26.2	1.190

NOTE (1) FLIGHT 4 ONLY

Figure 4-58

ECLIPSE SEASON NO.	MIN. VOLTAGE (V) RECOND. CAP. (AH)	RECONDITIONING DISCHARGE	LOAD RESISTANCE
		44 OHMS (S/N 3-6)	167 OHMS (S/N 3-3)
1	26.82 (1.219 V/CELL) RECOND. CAP. (AH)	26.82 (1.219 V/CELL)	27.00 (1.227 V/CELL) 19.3 12V
2	26.80 (1.218 V/CELL) RECOND. CAP. (AH)	26.80 (1.218 V/CELL)	26.85 (1.220 V/CELL) 19.5/12V
3	26.70 (1.214 V/CELL) RECOND. CAP. (AH)	26.70 (1.214 V/CELL)	26.90 (1.223 V/CELL) 19.3/12V
4	26.80 (1.218 V/CELL) RECOND. CAP. (AH)	26.80 (1.218 V/CELL) 14.5/19V	26.90 (1.223 V/CELL) 19.4 12V
5	26.80 (1.218 V/CELL) RECOND. CAP. (AH)	26.80 (1.218 V/CELL)	26.85 (1.220 V/CELL) 18.5 12V 18.0 12V

Figure 4-57

ECLIPSE SEASON NO.	CELL NO. FIRST TO REVERSE	TIME ON RECOND. DISCHARGE TO FIRST REVERSAL (HRS.)	CURRENT AT FIRST REVERSAL (A)	12-CELL PACK VOLTAGE (V)	NO. OF CELLS REVERSED AT EOD (~0.1V/CELL)
15	11	79	0.132 (C/180)	4.31 (0.36V/CELL)	9
23	1	77	0.277 (C/87)	8.10 (0.68V/CELL)	8
29	1	77	0.289 (C/83)	10.75 (0.90V/CELL)	8
33	1	69	0.285 (C/84)	11.35 (0.95V/CELL)	8

Figure 4-59

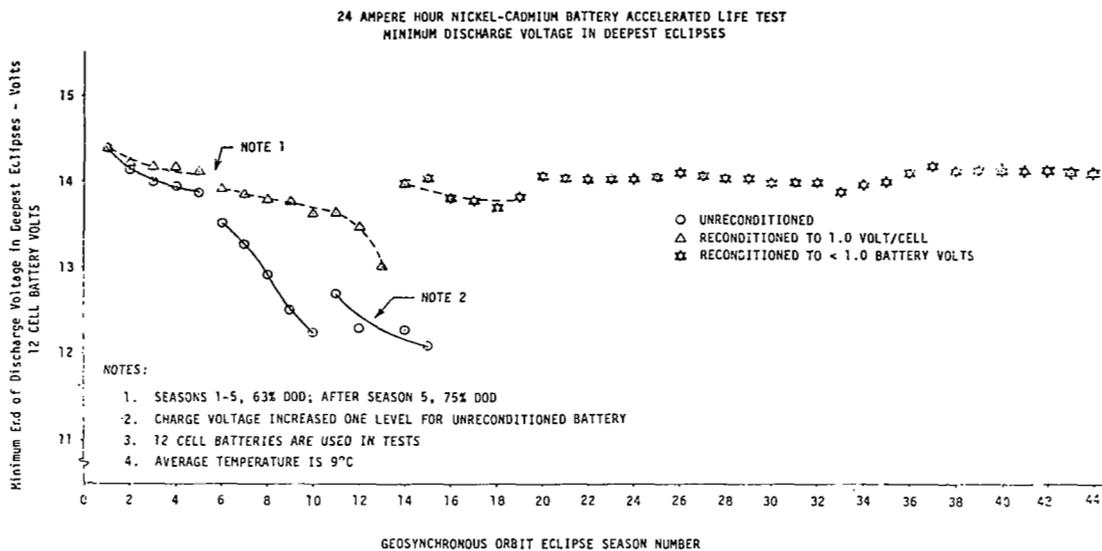


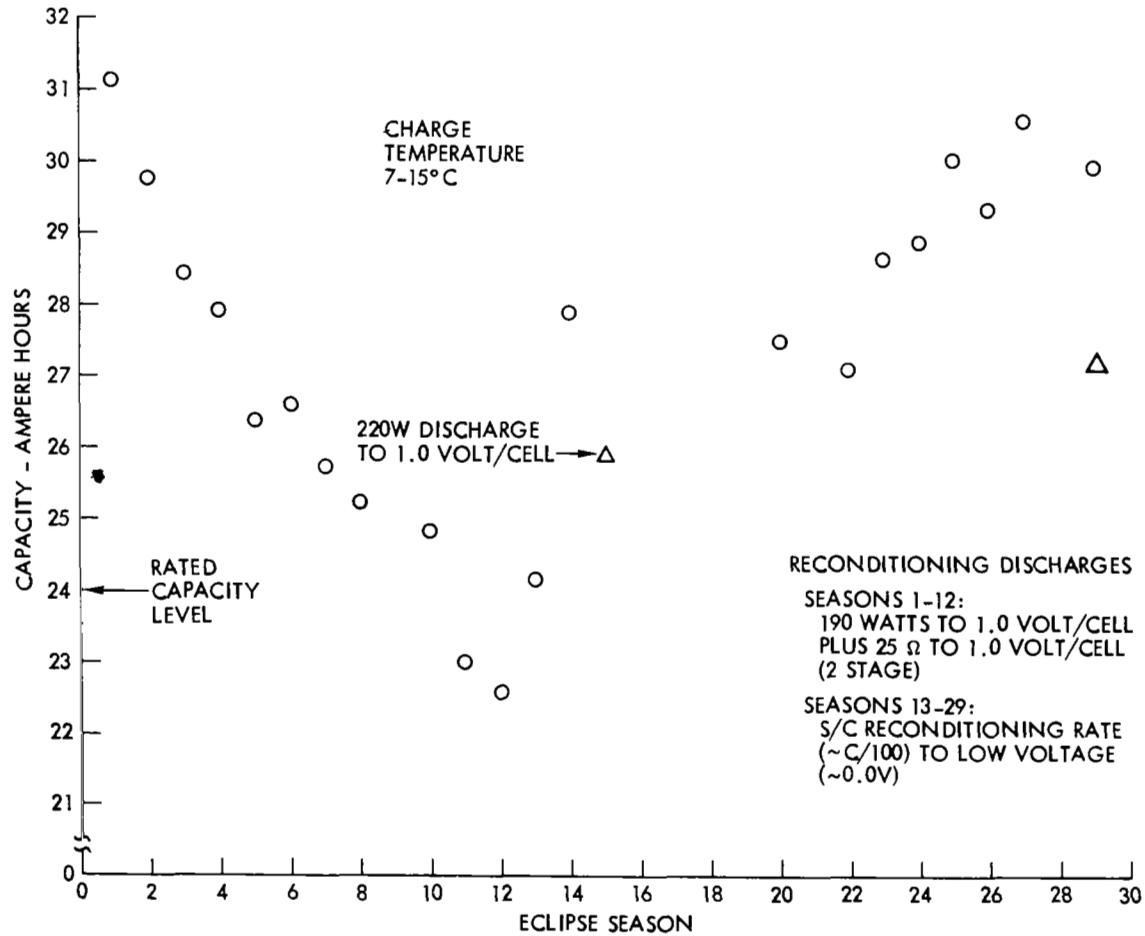
Figure 4-60

ECLIPSE SEASON No.	RECOND. PRIOR TO SEASON	CAP. ON RECOND. (1) DISCHARGE (AH TO 18V)	MINIMUM VOLTAGE DURING SEASON		
			BATTERIES	V/CELL	MAX. TEMP. (°F)
1	NONE	-----	27.8-27.9	1.158	63
2	ONE CYCLE	33.77-34.30	27.8-27.9	1.158	65
3	ONE CYCLE	34.10-34.72	27.8	1.158	65
4	ONE CYCLE	34.36-34.43	27.8	1.158	65

(1) 85 OHMS/24 CELLS

Figure 4-61

CAPACITY (AH TO 1V/CELL) ON RECONDITIONING DISCHARGES



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Figure 4-62

## ADDITIONAL REVERSAL CHARACTERISTICS OF SEALED NICKEL CADMIUM CELLS

P. Ritterman  
TRW

To change the topic slightly, additional remarks on reversal characteristics of sealed nickel-cadmium cells. I gave a paper on reversal characteristics of nickel-cadmium cells 2 years ago, and those were state of the art cells.

We have done some further testing on state-of-the-art cells, and we have done some design work to improve the cells from the standpoint of hydrogen-nickel combinations.

(Figure 4-63)

This is a background on nickel-cadmium reversal characteristics. Nickel-cadmium cells are positive limiting on discharge, and when they are completely discharged, hydrogen is evolved from the positive electrode. One ampere-hour of overdischarge in reversal can generate enough hydrogen to increase the cell pressure of an average size cell, a 20-to 50-ampere hour cell, by 120 psi.

On an ampere-hour basis, the theoretical hydrogen evolution is quite extensive. But it can be kept at a minimum and even at zero by selection of a low reversal rate. Constant current reversals on state-of-the-art aerospace nickel-cadmium cells have shown that a steady-state condition, a concentration condition exists at  $C/100$ , around that rate, a little higher, a little lower, and at  $20^{\circ}\text{C}$ .

(Figure 4-64)

I showed this vugraph 2 years ago, and I have shown it in subsequent papers. Your dotted lines show the theoretical pressure increase. That is, if you just have hydrogen resolution, that's the rate of pressurizer you would see. Actually, we demonstrated, and these are the average results of about 4 cells of each kind. We can overdischarge 12-ampere hour cells at as high a rate as 100 milliamperes, about  $C/100$ , and get pressure equilibrium. The pressure remains constant as we continue to overdischarge. We are plotting pressure versus overdischarge in ampere-hours.

With brand new 24-ampere hour cells, we were able to overdischarge at 400 milliamperes and still attain a pressure equilibrium at a slightly higher pressure. And this represents a  $C/60$  overdischarge rate.

I don't think the fact that 12-ampere hour cells are now new is as significant as the fact that the design of this 12-ampere hour cell is vintage 1970, and this one 1974. There were some slight changes.

(Figure 4-65)

Again this is review. It is a mechanism hypothesized to explain this constancy in pressure as cells are overdischarging.

When a positive cell has exhausted its capacity, hydrogen gas is generated at the positive electrode shown by equation 1. The negative electrode still has capacity, so cadmium continues to discharge to form cadmium hydroxide. The gas that is generated is directly proportionate to the overdischarge current by Faraday's laws.

Some of the gas migrates over to the negative electrode where it is absorbed on the active nickel sites of the negative electrode. So you have got hydrogen being absorbed on sintered nickel forming atomic hydrogen. The hydrogen is removed from the nickel sites by reaction with hydroxide at potential of the cadmium hydroxide electrode. So you remove hydrogen from the nickel and form water.

When you remove hydrogen by the reaction of hydroxide with atomic hydrogen, you have a charge. The cadmium is in intimate contact with the sintered nickel sites containing hydrogen. So the electron that is lost by reaction with hydroxide now reacts with cadmium hydroxide to charge the cadmium hydroxide to cadmium plus two hydroxides. The net reaction is a chemical charging of the cadmium hydroxide by the hydrogen to give you cadmium under water.

The recombination of hydrogen not only removes the gas, but also results in a chemical charging of the negative electrode. Therefore, when you have equilibrium, not only do you retain constant pressure, but you can never fully discharge the cadmium electrode, because as it is discharging electrochemically, it is charging chemically.

(Figure 4-66)

An application of hydrogen recombination. Reconditioning by shorting at a battery level to almost zero volts improves the battery characteristics. As Dr. Scott has shown, it extends battery life and also increases the minimum end-of-discharge voltage.

When shorting to zero volts, some of the cells of lower capacity are driven into reversal by the cells with higher capacity. By appropriate selection of a resistor size, pressure buildup is controlled in a reverse state of the art, nickel-cadmium cells.

Improved cells with greater hydrogen recombination capability would permit greater flexibility in choice of reconditioning resistor and reconditioning time. A significant increase in hydrogen recombination capability of nickel-cadmium cells would simplify the battery bypass circuitry, reduce costs, and weight, as well as increase life.

(Figure 4-67)

About 1 1/2 years ago, NASA/Lewis gave us a contract to study further hydrogen recombination, get some further evidence about the validity of the mechanism, optimize the parameters that affect hydrogen recombination without detrimentally affecting the capacity or life of a cell in normal use and develop nickel-cadmium cells capable of nondestructive high rate reversals. We are talking about really high rate reversals, gold C/2.

(Figure 4-68)

To further verify the hydrogen-recombination mechanism, we did some AC impedance-mechanism measurements in C2 during over discharge and while we had established equilibrium.

The objective of this was to show that there was no appearing or disappearing short that occurs in the cell that accounts for the constant pressure.

We did the following: We took five 10-ampere hour cells, overdischarged at 50 milliamperes for 40 hours, and we developed pressure equilibrium within the first 10 hours of overdischarge. And the pressure equilibrium was between 34 and 40 psia for the five cells.

The AC impedance measurements remained constant during the overdischarge. There was no short either before or after overdischarge as indicated by charge retention tests.

Finally, the strongest piece of evidence that we are not looking at a short, but we are looking at two hydrogen electrodes, one generating hydrogen, one recombining hydrogen, is that the cell voltage during overdischarge was between 10 and 20 millivolts, and the AC impedance was measured at 2.7 milliohms.

If the voltage were merely ohmic, the voltage that we show here, -10 to -20 millivolts, its value would be  $2.7 \times 10^{-3} \times 5 \times 10^{-2}$  or essentially 1/10 millivolt. The voltage that we see is actually two orders of magnitude greater and that seems to support two electrode reaction rather than a short.

(Figure 4-69)

Another thing we wanted to show is that hydrogen recombination that we see on open circuit is consistent specific to hydrogen and not merely the absorption of a gas on a high-surface area electrode.

We ran a couple of cells, and we switched them back and forth, but this is a typical result. A cell when filled with helium on open circuit stand – this is a discharge nickel-cadmium laboratory cell – showed practically no pressure decrease. A similar cell filled with hydrogen shows substantial decrease in pressure.

We switched the cells around, also, putting the hydrogen in one cell, helium in the other cell, and the same result occurred. That is to say, no change with the helium. Pressure decreased with hydrogen.

(Figure 4-70)

In order to improve hydrogen recombination, we looked at some of the parameters that, I and NASA Lewis believed, were controlling factors in the rate of hydrogen recombinations.

We looked at two modes of impregnating and negative electrode by electrochemical means and by vacuum. We looked at two levels of precharge on the negative electrode, 40 percent and 20 percent for the positive capacity.

We looked at the effect of electrolyte concentration, 32 percent and 28 percent. We looked at electrolyte fill; that is to say, the percentage of the residual pore volume that contains electrolyte. The residual pore volume of the core, positive, negative, and the separator. We looked at 80-percent fill and 100-percent fill. And finally we looked at the effect of interelectrode distance, 4 mils, 6 mils, and 8 mils.

We were able to control these parameters by measuring the porosity of the electrodes that we used, significant samples of the electrodes. We measured the residual porosity by water absorption, weighing dry and weighing wet, and we calculated the porosity of the separator.

We controlled the interelectrode distance by having a fixed interdistance on the laboratory cell, measuring each electrode, and then by subtraction calculation what the interelectrode distance with the total distance, what the amount of shim would have to be to maintain interelectrode distance of 4, 6, or 8 mils.

(Figure 4-71)

The parametric experiment was run in the following way. We had 18 different designs of nickel-cadmium cells, evaluated them for their capability of recombining hydrogen. We had two cells of each kind.

We overdischarged the cells at ever-increasing overdischarge rates, starting at C/100, and then the cells that were able to recombine hydrogen without going into overpressure or undervoltage, they continued on to the next highest rate. But between the time of overdischarges, we readjusted the precharge to its original value by charging the cells and venting oxygen.

The experiments for cells made with electrochemically impregnated negatives have been completed. What we have achieved there is an optimum hydrogen recombination rate of C/20 which is three times as high as anything achieved in the state of the art with cadmium cells.

The design parameters were 6-mil interelectrode distance, 40-percent recharge, 32-percent electrolyte and 100-percent electrolyte fill.

I am aware that yesterday a statement was made regarding the optimum rate that we achieve is C/2. We did, indeed, do this. The work is going on right now with vacuum impregnated negative

electrodes. We have achieved this in quite a few cells. But I am not ready to go into the details of this. That will be the subject of some future paper.

(Figure 4-72)

For the two cells of optimum design, we plotted equilibrium pressure versus overdischarge rate, and each data point represents the pressure where the cells remained constant during a particular overdischarge rate.

We see that cell equilibrium pressure is directly proportional to overdischarge rate and essentially the two curves pass pretty close to the origin, zero, which is in agreement with the hydrogen recombination hypothesis.

(Figure 4-73)

Here's a summary of the different values attained under different conditions, different values of hydrogen recombination rate expressed at the current density under different test conditions; open circuit, best state-of-the-art, nickel-cadmium cell gives you a recombination current density of 0.43 milliamperes per square decimeter. That's the geometric surface area of the negative electrode of that cell.

The best laboratory cell, or laboratory cell unoptimized, gives us about the same thing, 0.33 milliamperes per decimeter squared.

During discharge where the potential of the negative is more favorable to hydrogen recombination, we have an order of magnitude increase in the hydrogen recombination rate from 0.3 to 3.0 going from open circuit to discharge.

When we go to overdischarge, the best state-of-the-art nickel-cadmium cell is 36, unoptimized laboratory cell is 9, the optimized laboratory cell is 93. So we have a threefold increase.

If we consider the data we obtained with the vacuum impregnated cells, we have 900 milliamperes per decimeter squared that we have attained, but that will not be discussed today.

(Figure 4-74)

Our future work on this contract is completion of the parametric experiment for vacuum impregnated cells, vacuum impregnated negatives. As to the optimization with relation to active material loading, we are going to look at loading levels on the negative electrode of 2.1, 1.8, and 1.4 grams per cc void, and evaluate as we did before, ever-increasing overdischarge-rates.

We will then fabricate 24 identical optimized laboratory cells and subject them to geosynchronous orbit cycling with periodic reversals and sequential removal of cells for teardown analysis at the end of each season.

The teardown analysis will consist of determining electrolyte distribution, electrolyte concentration, plate capability – that is flooded capacity of the plate – undischageable cadmium, physical dimensional changes of the electrodes, separator condition and thickness. And finally that should be one dot out here.

As a follow on to this work, we would procure and have fabricated flight type cells of the optimum design, and we would then test as a battery.

## DISCUSSION

KILLIAN: Paul, you showed very different recombinations depending on whether it was open circuit discharge or overdischarge slide. Do you have an explanation for that?

RITTERMAN: Yes. On discharge you have a polarization of a negative electrode, which favors hydrogen recombinations, and have bigger delta V between the hydrogen cell and the cadmium hydroxide cell. Open circuit you have a very small potential difference. You have got 20 millivolts.

With respect to overdischarge – and this is something I have observed – the electrolyte seems to disappear on overdischarge, decreasing the thickness of the diffusion layer and making the hydrogen more accessible to the cadmium electrode.

SCHULMAN: How important is this state of precharge on this recombination mechanism?

RITTERMAN: You mean the amount of charged cadmium that's left?

SCHULMAN: Yes. I thought I heard you mention that you had to sort of rejuvenate the precharge.

RITTERMAN: You have got to understand what I am doing here. I am overdischarging my cell at various rates. For example, I overdischarge at C/100 and I develop 50 pounds of hydrogen pressure. Okay?

I don't want to wait and sit around until that hydrogen recombines, so what I do is pump the hydrogen out and I say that hydrogen is equivalent to a certain amount of ampere-hours of negative precharge, and I hold the cell. I have got to return to the cell.

So, in order for me to go on to the next reversal rate at the same state of charge of the negative electrode that I was in initially, I have got to charge up that cell, overcharge it, and then to oxygen and then get back to the original state. Then I short the cell down and I have got the cell in a state that I was in before I had the previous overdischarge.

O'SULLIVAN: Could you tell us where the electrochemical plates were from? If there was any nickel hydroxide in the negatives?

RITTERMAN: They were made by GE. This is for the parametric tests we are talking about. There is another manufacturer, Gulton. But for the parameteric tests made by electrochemical impregnation at GE. And to my knowledge, no intentional nickel hydroxide is in there.

O'SULLIVAN: Where they analyzed for it?

RITTERMAN: No, they were not.

HARKNESS: Paul, one question on the 24 cells you are going to make, will they be electrochemically impregnated?

RITTERMAN: Probably not, based on results that we are not ready to report on. But based on the C/2 rate, they would not be electrochemically impregnated, but they would be vacuum impregnated.

NEWELL: Were you concerned about the electrolyte concentration when you were venting hydrogen and oxygen?

RITTERMAN: I gave that some thought. The change was very slight. Water weighs 18, and 18 is 26 ampere-hours, so you have a relatively small change based on the amount of electrolyte we had in there. But, no, I did not provide for that small change.

GROSS: When you forced the cell into overdischarge, this sets up a driving force which tends to plate out cadmium and increase the likelihood of shorting. This becomes a greater problem, especially when the cell gets old and has been observed on discharge of old cells.

It would seem therefore, that in the optimization of the whole design, in looking at the whole problem, this aspect of the problem would certainly have to be taken into account.

RITTERMAN: I don't know if I can just answer with a simple yes or not, but I think cadmium was more likely to do this on overcharge than overdischarge.

GROSS: It occurs on overdischarging.

RITTERMAN: Are you saying that the cadmium is plating out of the positive electrode toward the negative electrode?

What you are doing is that you are driving the positive electrode to the potential of cadmium hydroxide. Is there a cadmium hydroxide in the electrolyte, is what you are saying that tends to plate out?

GROSS: If, for example, you had cadmium hydroxide on the nickel positive....

RITTERMAN: Deliberately put in there?

GROSS: Let's say it's there by migration. Then it will be reduced cadmium. If it is then in contact with cadmium hydroxide in the separator, it will reduce that and that could accelerate. You are shorting through the separator giving you a cadmium dendrite.

RITTERMAN: Right. But the negative electrode is all cadmium, and when you charge that, it is a much more favorable reaction to occur – growth from the cadmium out toward the positive and there is very rarely a short on overcharge.

GROSS: That's another problem, but that's not the problem we are addressing. The problem we are addressing is the tendency for cadmium to short out the cells on overdischarge. There is no question that there is a driving force; there is no question that it sometimes happens especially in old cells. The problem is to properly take that risk into account.

RITTERMAN: I think we are going around in circles now. I will discuss it with you privately if you wish.

GOUDOT: Did you check the curve of evolution of gas as a function of DOD?

RITTERMAN: I am sorry – you are saying the evolution of gas as a function of DOD?

GOUDOT: Yes.

RITTERMAN: Well, there is no evolution of gas under the normal DOD.

GOUDOT: No. When you made the cycle with different DOD and going in a reverse way, did you observe a plateau, for instance?

RITTERMAN: These parametric testings were new cells. We did nothing to them except give them 30 conditioning cycles and then start the reversal right away.

GOUDOT: But did you observe a plateau before, a relaxed time before evolution of gas due to that?

RITTERMAN: Are you saying a residual time to antipolar mass, or what?

GOUDOT: Nonfunction of DOD in the cycling.

RITTERMAN: There is no DOD.

GOUDOT: It is 100 percent each time?

RITTERMAN: 100-percent discharge, yes. And then overdischarge. We start out okay, and we set precharge on the cell, initially at 40 percent, for example. We then discharge the cell completely, we short it down, we proceed to overdischarge, and we get a certain amount of hydrogen there at an equilibrium pressure.

Rather than wait for hydrogen to recombine and return the cadmium to its original state of charge, we vent the cadmium, charge the cell all the way up again, and vent the oxygen — this time to reset the precharge to its original value, and we know this because we know the value of the pressure of hydrogen. So half that pressure of oxygen is needed to reset the precharge. We short the cell down again, and then we start the overdischarge.

So, each time we start out with a completely discharged cell with respect to the positive electrode and at the same precharge with respect to the negative electrode.

LACKNER: I just wanted to get a clarification on your terminology, “100-percent electrolyte fill.” Is there some way you could translate that into cc’s per ampere-hour?

RITTERMAN: No. You could, but it wouldn’t mean anything because the residual porosity of electrodes vary. What we did is, measure the porosity of a good sample of the electrodes that we used, residual porosity.

LACKNER: You are filling all available pores, then?

RITTERMAN: We are filling all available pores, yes. We can calculate the porosity of the separator. It is under specific compression of the interelectrode distance that we set.

LACKNER: That’s the porosity of the plate originally not taking into account any changes that might have taken place?

RITTERMAN: I take the original porosity. I don’t preswell the plates or anything like that.

- POSITIVE LIMITING NI-Cd CELLS EVOLVE HYDROGEN WHEN DRIVEN INTO REVERSAL.
- ONE AMPERE HOUR OF REVERSAL RESULTS IN SUFFICIENT HYDROGEN EVOLUTION TO INCREASE PRESSURE 120 PSI.
- ON AN AMPERE HOUR BASIS THEORETICAL HYDROGEN PRESSURE BUILDUP DURING REVERSAL IS EXTENSIVE, HOWEVER, IT CAN BE KEPT AT A MINIMUM AND EVEN AT ZERO BY SELECTION OF LOW REVERSAL RATE.
- CONSTANT CURRENT REVERSAL USING AEROSPACE NI-Cd CELLS HAVE SHOWN THAT A STEADY STATE CONDITION IS ACHIEVABLE AT C/100 AND TEMPERATURES OF 20°C.

Figure 4-63

HYDROGEN RECOMBINATION MECHANISM

- WHEN THE POSITIVE ELECTRODE HAS EXHAUSTED ITS CAPACITY, HYDROGEN GAS IS GENERATED WITHIN THE CELL AT THE POSITIVE ELECTRODE
  - (1)  $2 H_2O + 2OH^- + H_2$   
AND WHILE NEGATIVE ELECTRODE IS DISCHARGING
  - (2)  $Cd + 2OH^- \rightarrow Cd(OH)_2$
- THE  $H_2$  GENERATED IS DIRECTLY PROPORTIONAL TO THE OVERDISCHARGE CURRENT
- SOME OF THE HYDROGEN GAS MIGRATES OVER TO THE NEGATIVE ELECTRODE WHERE IT IS ADSORBED ON THE SINTERED NICKEL SITES
  - (3)  $H_2 + Ni \rightarrow 2H(Ni)$
- HYDROGEN IS REMOVED FROM THE NICKEL SITES BY REACTION WITH HYDROXIDE AT THE POTENTIAL OF THE  $Cd/Cd(OH)_2$  ELECTRODE
  - (4)  $2 H(Ni) + 2 OH^- \rightarrow 2 H_2O + 2 e^-$   
WHILE  $Cd(OH)_2$  IS REDUCED TO Cd
  - (5)  $Cd(OH)_2 + 2e^- \rightarrow Cd + 2 OH^-$   
FOR A NET REACTION OF (3) + (4) + (5)
  - (6)  $Cd(OH)_2 + H_2 \rightarrow Cd + 2 H_2O$
- THE RECOMBINATION OF HYDROGEN NOT ONLY REMOVES THE GAS, BUT ALSO RESULTS IN "CHARGING" OF THE NEGATIVE ELECTRODE
- WHEN THE RATE OF HYDROGEN GENERATION EQUALS ITS RATE OF RECOMBINATION, EQUILIBRIUM IS REACHED AND THE CELL CAN BE OVERDISCHARGED INDEFINITELY WITHOUT CHANGE OF PRESSURE OR STATE OF CHARGE

Figure 4-65

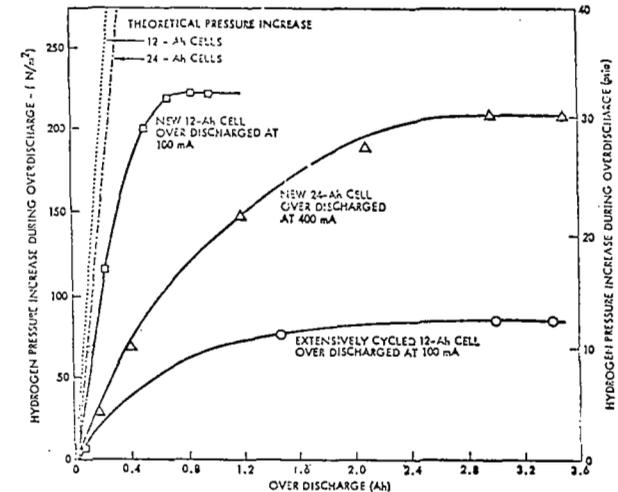


FIGURE 3.

Figure 4-64

APPLICATION OF HYDROGEN RECOMBINATION

- RECONDITIONING BY SHORTING AT A BATTERY LEVEL TO ALMOST 0.0V BATTERY VOLTAGE HAS RESULTED IN:
  - EXTENSION OF BATTERY USEFUL LIFE
  - INCREASE IN MINIMUM END OF DISCHARGE VOLTAGE
- WHEN SHORTING TO ALMOST 0.0V, ON A BATTERY LEVEL CELLS OF LOWER CAPACITY ARE DRIVEN INTO VOLTAGE REVERSAL
  - BY APPROPRIATE SELECTION OF RECONDITIONING RESISTOR SIZE, PRESSURE BUILD UP IS CONTROLLED IN REVERSED STATE OF THE ART CELLS
  - IMPROVED CELLS WITH INCREASED HYDROGEN RECOMBINATION CAPABILITY WOULD PERMIT GREATER FLEXIBILITY IN CHOICE OF RECONDITIONING RESISTOR AND RECONDITIONING TIME
- A SIGNIFICANT INCREASE IN HYDROGEN RECOMBINATION CAPABILITY OF NI-Cd CELLS WOULD SIMPLIFY BATTERY BY PASS CIRCUITRY, REDUCE COST AND WEIGHT AS WELL AS INCREASE LIFE

Figure 4-66

- OBJECTIVES
  - VERIFICATION OF THE HYDROGEN RECOMBINATION MECHANISM.
  - OPTIMIZATION OF DESIGN PARAMETERS THAT EFFECT RATE OF HYDROGEN RECOMBINATION WITHOUT DETRIMENTALLY EFFECTING NORMAL CELL PERFORMANCE.
  - DEVELOPMENT OF Ni-Cd CELLS CAPABLE OF NON-DESTRUCTIVE HIGH RATE REVERSAL.

Figure 4-67

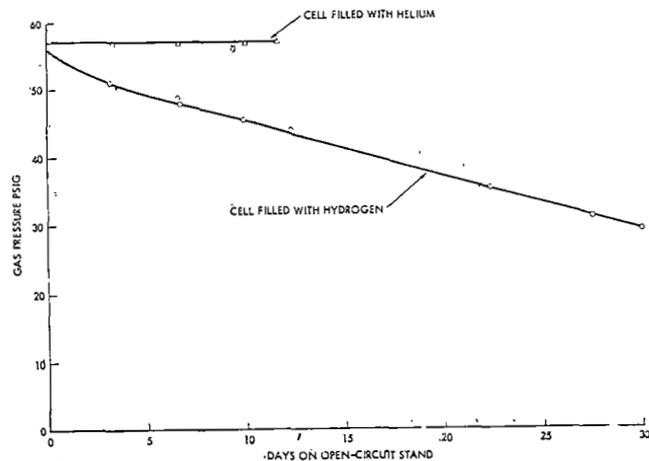


Figure 4-69

- AC CELL IMPEDANCE MEASUREMENTS
  - FIVE 10 AH CELLS OVERDISCHARGED AT 50 mA FOR 40 HOURS DEVELOPED EQUILIBRIUM PRESSURES BETWEEN 34 AND 41 PSIA AFTER THE FIRST 10 HOURS OF OVERDISCHARGE.
  - AC MEASUREMENTS REMAINED CONSTANT DURING OVERDISCHARGE.
  - NO SHORT PRIOR TO OR AFTER OVERDISCHARGE AS INDICATED BY CHARGE RETENTION TESTS.
  - CELL VOLTAGE DURING OVERDISCHARGE BETWEEN -10 AND -20 mV, WHILE A.C. IMPEDANCE MEASURES AT 2.7 MΩ. IF VOLTAGE WERE MERELY OHMIC ITS VALUE WOULD BE,  $2.7 \times 10^{-3} \times 5 \times 10^{-2} = 1.35 \times 10^{-4}$  V OR ~.1mV.
  - ALL RESULTS SUPPORT THE POSTULATED HYDROGEN RECOMBINATION MECHANISM.

Figure 4-68

Method of Negative Electrode Impregnation	Precharge %	Electrolyte Concentration %KOH	Electrolyte Fill = 80%			Electrolyte Fill = 100%		
			Interelectrode Distance (mil)			Interelectrode Distance (mil)		
			4	6	8	4	6	8
Electrochemical	40	32	-	n = 2	n = 2	-	n = 2	n = 2
	20	28	n = 2	-	-	-	-	-
Vacuum		32	-	n = 2	n = 2	-	n = 2	n = 2
	40	32	-	n = 2	n = 2	-	n = 2	n = 2
	20	28	n = 2	-	-	-	-	-
		32	-	n = 2	n = 2	-	n = 2	n = 2

n = number of cells

Figure 4-70

• PARAMETRIC EXPERIMENT

- 18 DIFFERENT DESIGNS OF NICKEL CADMIUM CELLS EVALUATED FOR THEIR CAPABILITY TO RECOMBINE HYDROGEN.
- CELLS OVERDISCHARGED AT EVER INCREASING RATES  
C/100 C/50, C/20, C/5, C/2
- OVERDISCHARGE TERMINATED WHEN CELLS REACH OVERPRESSURE (60/120 PSIA) OR UNDERVOLTAGE (-0.5V).
- EXPERIMENTS FOR CELLS MADE WITH ELECTROCHEMICALLY IMPREGNATED NEGATIVES HAVE BEEN COMPLETED.  
DESIGN WITH OPTIMUM HYDROGEN RECOMBINATION (C/20 ACHIEVED)  
5 MIL INTERELECTRODE DISTANCE  
40% PRECHARGE  
32% ELECTROLYTE  
100% ELECTROLYTE FILL

Figure 4-71

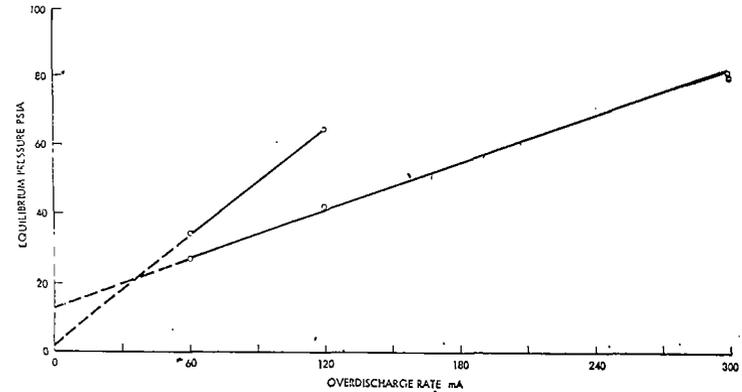


Figure 4-72

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CONDITION	CELL	CURRENT DENSITY*
OPEN CIRCUIT	BEST STATE OF THE ART Ni-Cd	0.43 mA/DM <sup>2</sup>
	LABORATORY Ni-Cd (UNOPTIMIZED)	0.33 mA/DM <sup>2</sup>
DISCHARGE	LABORATORY CELL (UNOPTIMIZED)	3.0 mA/DM <sup>2</sup>
OVERDISCHARGED	BEST STATE OF THE ART Ni-Cd	36.4 mA/DM <sup>2</sup>
	UNOPTIMIZED LABORATORY CELL	9.4 mA/DM <sup>2</sup>
	OPTIMIZED LABORATORY CELL	93.8 mA/DM <sup>2</sup>

\*AT PRESSURES OF 50-80 PSIA

Figure 4-73

- COMPLETION OF PARAMETRIC DESIGN EXPERIMENT
- OPTIMIZATION WITH RELATION TO ACTIVE MATERIAL LOADING OF NEGATIVE ELECTRODE
  - LOADING LEVELS  
2.1 g/cm<sup>3</sup>, 1.8 g/cm<sup>3</sup>, 1.4g/cm<sup>3</sup>
  - EVALUATE AT C/100, C/50, C/20, C/5, C/2 OVERDISCHARGE RATES.
- FABRICATION AND CYCLING OF 24 IDENTICAL OPTIMIZED LABORATORY CELLS
  - SIX SEASON OF GEOSYNCHRONOUS ORBIT WITH PERIODIC REVERSAL
  - SEQUENTIAL REMOVAL OF CELLS FOR TEARDOWN ANALYSIS
- TEARDOWN ANALYSIS OF CELLS
  - ELECTROLYTE DISTRIBUTION
  - ELECTROLYTE CONCENTRATION
  - PLATE CAPABILITY
  - UNDISCHARGEABLE CADMIUM
  - PHYSICAL DIMENSION OF ELECTRODES
  - SEPARATOR CONDITION AND THICKNESS
  - FABRICATION AND TEST OF FLIGHT TYPE CELLS OF OPTIMUM DESIGN

Figure 4-74

## REVERSAL OF NICKEL CADMIUM CELLS

C. Badcock  
Aerospace

We have been doing a limited number of experiments right along. We don't vent the hydrogen off in general over the last year or year and a half with two cells. I need to emphasize that these are a different design nickel-cadmium cell, the same manufacturer that Paul has been talking about. We have seen some different behavior that I would like to report.

(Figure 4-75)

The areas I am going to talk about, first, is a mistake that gave us some information. Second, most of the time is misspent looking at the kinetics of the reaction of hydrogen on open circuit stands after high-rate reversal of the cell. We are talking about high rate here as  $C/5$ . And, finally, we have looked briefly at the pressure voltage profiles during low-rate reversal, similar to what Paul has been saying.

I need to emphasize the order we have done the experiments in, which may have a bearing on it, is as shown here.

(Figure 4-76)

The two cells we have been working with are as described here. They have a common case in negative. We merely turned the little copper connector solder lug off the top of the cell, drilled 1/16 inch hole into the interior itself, and hooked up a pressure transducer with the valve.

(Figure 4-77)

We have seen no effects of that type of procedure in the behavior of the cell.

First hydrogen – the study of hydrogen addition to a cell. We set the thing up and were cycling it, but it developed a leak in the plumbing, causing us to lose the precharge. So, by having a cell with no precharge in it, we had a problem and we simply added hydrogen to it to regenerate the precharge.

I have shown how much precharge we measured by electrochemical means just in the cell. This is a starved cell. It was not opened, indicating the reactions as Paul indicated. It goes as shown with that type of stoichiometry.

What I would like to point out, you will see later, is the rates we observed for hydrogen recombination. Those are in reciprocal hours. These are not rapid experiments.

(Figure 4-78)

The second area has to do with the effects of high-rate reversal on the cells and subsequent pressure, hydrogen pressure loss. The regime that we have adopted for these experiments is shown. Most of the time we charged the cell up and measured the capacity. That's simply what the first two steps are for.

Notice that for a particular experiment, we would charge it for 1 hour at the two-ampere rate, C/5 rate, and then drive it into reversal or whatever the pressure is that we wish to start it at was. Then switch the cell open circuit and continuously monitor all those good things.

We corrected all the pressures to 24 degrees so they could be compared. The temperatures we used were shown. 22 degrees was not in the thermostat, so the swing was plus or minus 2 degrees.

(Figure 4-79)

During the reversal, we see a variety of types of behavior. We see initially no pressure increase in the voltages shown below. This, we assume, is from one of two things: either cadmium-hydroxide in positive electrode or residual nickel oxide positive capacity that is being discharged out.

Then we have a slowly changing voltage. Then we see a very, very high linear pressure increase. The slope of that line is about 80 percent of the theoretical we predicted and was all being converted into hydrogen. One thing you can note from that line is where the other 20 percent is. We are not sure, but it certainly isn't by first order of combination of hydrogen, or it would curve over. But it is straight.

I will show the recombination hydrogen reaction curves here that bear some correlation to that. However, we do not always see that step, the plateau in pressure at the first of the reversal, as is shown here where it turns up quite rapidly. The slope of this line and this line are different, and these are different reversals. These are the same.

In fact, no matter what the current is and we have a pressure rise like this, we see the same slope in that line, whether it be 2 amperes or 100 milliamperes.

(Figure 4-80)

The loss of pressure now – we have two sections that I have shown – we have good first-order kinetics after about 24 hours, and the line shown there is more linear regression on that first-order kinetics section. Before that we always see a higher rate.

It is totally uncorrelatable in order with hydrogen.

The interesting thing is that the initial slope of this line is very similar to the slopes of these lines.

It may well be that we have clearly another process going on. The time would indicate to me that it is not pressure that is causing this increase rate — I mean it's not oxygen. I don't know where we would get the oxygen in this case. It's not temperature because of the duration, and the fact that these experiments are done in a thermostat with good thermal control.

(Figure 4-81)

Summarizing the data over the temperatures, we get a little bit better than a factor of two. Repeatability between experiments. Notice the pressures that we have been running into, some in excess of 300 pounds.

Our objective in these experiments initially was that if you ever got in that situation, what do you do about it. Our conclusion so far is not much.

Notice the experiment numbers here are the order of experiments shown, so that nine is the last experiment in the capacity frequently. I have also added in here our rate constants for hydrogen additions. This is done only on one cell. We got only one leak.

Notice the comparison between the 22 degrees and 22 or 24 degrees here and the rate constants. One of these experiments, I believe it was seven, was done with the cell short circuited rather than open circuit for part of the time. We saw no difference in the rate.

(Figure 4-82)

Again, this is just an Arrhenius plot showing the temperature dependence, and I think this agrees quite well with Paul's statement which he's previously seen for open circuit reactions.

Having done that and getting these cells at very high pressures, we begin to ask, what can we do about it?

(Figure 4-83)

The first thing we tried was to reverse the cell at high rate to a given pressure and then to switch to a low-reversal curve and to watch what would happen.

What happens is that we see an initial rapid pressure decrease here, correlating with what I showed you before on the first-order plot. This rapid decrease in pressure initially occurred after a reversal, then a rise with a slope in this line, psi per ampere-hour is equal to the slope at 2-ampere rate, and then a falloff in pressure, first order of decay.

This is the voltage down here. You can see that the voltage behavior comes up and becomes constant at very near zero on the order of 10 to 30 millivolts. If we increase the reversal current to 200 milliamperes, it increases in what is essentially an ohmic fashion. In both cases, you notice that the two cells are not alike, but we have similar behaviors.

At the point when the pressure had decreased to essentially a few psi, we then measured the ohmic behavior in this, called "Ohm's Law" both in the reversal direction, in the charge direction as long as the current wasn't too low to leave it in the charge direction very long, that short immediately opens, and everything looks fine.

We subsequently started from a fully charged cell and discharged it constant current at 100 milliamps, which is  $C/100$ . We again see the pressure buildup and this type of voltage behavior, and then the cell apparently shorted. Now, what I am talking about a short here is that we get "Ohm's Law" behavior for current flow in both directions through zero.

Under other conditions, we have tried to do this on a cell we know is open circuited. We don't get that kind of behavior at all. So we would interpret that as being short.

(Figure 4-84)

Summarizing, in all of our experiments, actually the first thing is, in high rate reversal, we have never seen any shorting. These cells are open circuit, and they behave like an open circuit cell.

If we reverse to say 150 psi, the voltage will slowly wiggle around like this to a positive 1.2 volts on open circuit. If you really reverse it hard, it will stay very near zero for as long as you allow these to run and until the pressure is down. But we've never seen shorting.

However, when we go to low rates,  $C/50$ ,  $C/100$ , we have reproducibly seen shorting. Furthermore, the rates of hydrogen loss in these cells after you have established the pressure someplace are essentially the same whether the cell is under low rate reversal conditions, open circuit, or internally or externally shorted.

Finally, what we think is an ohmic short can be destroyed simply by allowing the cell to stay in open circuit or putting it on charge. And we have seen no ill effects. We still have the capacity we started with in these cells after about a year and approximately ten reversals. So we had good voltage behavior, and we have seen no real ill effect of this repeated high pressure reversal in the cells.

## DISCUSSION

**BADCOCK:** I would like to ask Paul a question, and he's going to ask me one on his cells. Did you have any problems with overcharged pressures on your cells with large amount of electrolyte in them?

**RITTERMAN:** No. It's not really a large amount of electrolyte when you consider 100-percent fill. It's not based on any ampere-hours.

Now, may I ask you a question? You showed a curve where you had a very high recombination rate initially an open circuit. If you would show that again — you showed a pressure

decay of hydrogen versus time on open circuit. That's very high. That initial part, is that what you obtained immediately after you reversed the cell?

BADCOCK: Yes, that's immediately after we had reversed the cell on open circuit.

RITTERMAN: So, wouldn't that be a residual effect of the higher rate, the high reserve, anyway?

BADCOCK: That is a very good point. I think it would be — I wondered why we haven't seen the same type of effects that you have in many instances. And I think that this and the less than theoretical slope on the lines during reversal have bearing on — that we have another mechanism going on in these cells.

Now, why haven't we seen it in these cells? I should have mentioned the age of these cells. They were about 5 years old. We had only about 200 cycles on them when we started. They also have puffy tops on them. Now, that's been corrected in the volume because of the high pressures. But again no problem.

RITTERMAN: What was the separator?

BADCOCK: These are polypropylene separated cells.

RITTERMAN: I don't know if it would make a difference, but all my tests were done with pellon separators.

BADCOCK: I understand.

ARMANTROUT: Chuck, I assume you had the same negative electrode in your cells as Paul did?

BADCOCK: No. I would like to tell you whether it had a silver additive or not, but I am not sure.

ARMANTROUT: Would you speculate as to what might have happened had your electrodes been teflonated?

BADCOCK: No.

ARMANTROUT: I did not find hydrogen recombination with teflonated negatives.

BADCOCK: Did you wait long enough?

ARMANTROUT: Yes. I found ultimately some recombinations, but I didn't find a plateau. The slope was going right up.

BADCOCK: Remember, we have not seen a plateau at any high rate. At low rates, the only time we see a plateau is when we would interpret the cell starting to short.

We were looking for that intermediate behavior Paul has reported on. We haven't seen that in this case.

RITTERMAN: What you have always done though is that you have gone from a high rate overcharge, switched down to either open circuit or a low rate overdischarge. Is that correct? High rate over discharge and then shut down to low rate?

BADCOCK: We have seen exactly the same behavior as when we started with a fully charged cell at constant current discharge, C/100, and took it all the way down and into reversal. That was our simulation of reconditioning.

RITTERMAN: The new cell that you ran these tests on, were they the exact same history as far as you know?

BADCOCK: Yes. Came out of the same cell pattern.

SEIGER: Could you tell me what the precharge is on these cells, and also what the interelectrode spacing was?

BADCOCK: I can't answer the interelectrode spacing. It was essentially 8- or 10-mil, polypropylene in these cells. The precharge is set at about 5 ampere-hours in these cells. That's about 25 percent of the total negative electrode capacity.

We have measured, in some cases, that there's greater than 2.9 ampere-hours, because that's how much we needed to get to that pressure.

SEIGER: Would you suspect that any of the positive electrodes would have swelled to alter the interelectrode spacing?

BADCOCK: Yes, I do expect a little bit. I can't answer these questions until we are through with these cells and cut them apart. But they are test specimens right now, so we don't want to violate them.

LIM: Can you extract activation and energy from your Arrhenius plot?

BADCOCK: Yes. It was 14 plus or minus about 2k cals per mole.

SCOTT: Can you say in general or in particular, how many ampere-hours total reversal that you had at these various rates when you saw the shorting pattern?

BADCOCK: On the one where we reversed a cell from full charge, took it into reversal at 100 mils, we had less than 2-ampere hours reversal in the cell, considerably less than that.

In general, it has been between 2 and 3, 3 1/2 ampere-hours when we have seen them, what I interpret as short.

RITTERMAN: Chuck, you showed some pressure buildup at C/5 discharge rates. You said you got about 80 percent of the pressurizer you expected to get. You also stated there was no short during that time.

BADCOCK: Yes.

RITTERMAN: Would you attribute the other 20 percent to hydrogen recombination?

BADCOCK: I can't say that. I should emphasize that not only did we see that same slope in psi per ampere-hour at 2 amperes, but also we see it at 100 milliamperes. If it is hydrogen recombination occurring during that time, it is not dependent on the pressure of hydrogen, which is certainly a reasonable thing to assume in some cases. If your coverage is near 100 percent . . . .

RITTERMAN: The one you have got to be aware of is that you do have an unaccounted for coulombic anomaly. If it isn't hydrogen recombination and there isn't a short, where did that 20 percent go?

BADCOCK: I would like to know.

GROSS: I presume that the activation energy that you calculated agrees with the cadmium hydroxide reduction. Is that correct?

BADCOCK: I don't know that. I have been looking for what that activation energy is. I know it's not diffusion or hydrogen. It is to slow wrong activation energy. I think it is the H<sub>2</sub> or H adsorb electrochemical reaction that has that thermal activation energy. There is some literature which would indicate that. I think that's what it is, but I'm not sure.

GROSS: I wonder also, if perhaps you had calculated and extrapolated an Arrhenius curve to get the activation energy at the very beginning of the recombination where you had a much higher slope, possibly try to pick out what reaction that might have been.

BADCOCK: To do that, you must have a constant order in the kinetics. The problem is when I tried to do a log/log plot to determine the order of the kinetics there, I get numbers between a 4 and 10 for order and hydrogen. So there is a problem there, and it is not constant.

I should point out that area is not constant enough in rate so one can do anything with it. It is not that predictable. It occurs every time, but not in a reproducible or predictable fashion.

SEIGER: Paul Ritterman had said something about the disappearing of the electrolyte when he went into reversal. I have observed it, and others have observed it. Perhaps during that initial period of time, the area involved in the recombination is different than it is a little later on.

BADCOCK: We have some data that we have to process yet and some other data to bear on that. The interpretation becomes a lot more complex than one would wish, and that's why I am not discussing that.

SEIGER: It might not be chemical. It might be something physical.

BADCOCK: Yes.

RITTERMAN: Again, going back to that log plot that you showed, I am not quite sure whether you said that initial high rate of recombination occurs only immediately after extensive overdischarge, or it would occur when you had a cell sitting in a completely discharged state for a while, dormant, and you added hydrogen?

BADCOCK: When we have added hydrogen to the cell, it does not occur. It is related to the high rate – at least our data indicate that it is related to the high rate of reversal.

RITTERMAN: You mean it is related to some intermediate situation?

BADCOCK: Obviously, one explanation for this is that during a reversal you generate reactive sites that recombine hydrogen very efficiently. But they are lost very rapidly. What you are seeing there is a loss in a number of active sites. That is a nice thing. We haven't anything to demonstrate that, but that is a nice explanation because it agrees with a less-than-theoretical slope during the reversal itself.

RITTERMAN: Only under the conditions where you shut off the cell after extensive reversal did you see that?

BADCOCK: That's correct. I guess one comment I would like to make. I think these data show you the range that one might expect in cells for the behavior during or after reversal. I don't disagree with the TRW position on the effects of reversing a cell. But if you are planning to do that, I think that every cell design, and hopefully the lot that you are using, is tested to make sure that you get their behavior rather than my behavior.

### Area of investigation

- ADDITION OF H<sub>2</sub> TO A CELL (open circuit)
- KINETICS OF H<sub>2</sub> REACTION ON OPEN CIRCUIT STAND FOLLOWING HIGH RATE (C/5) REVERSAL
- PRESSURE AND VOLTAGE PROFILES DURING CONTINUOUS LOW RATE REVERSAL

Figure 4-75

### H<sub>2</sub> Addition to a Cell

- CELL WAS CYCLED: 2.5 Ah CHARGE @ 2 amp  
2 Ah REVERSAL @ 2 amp  
12-hour OPEN CIRCUIT STAND
- LEAK CAUSED LOSS OF PRECHARGE TO APPROXIMATELY 1 Ah
- H<sub>2</sub> ADDED TWICE FOR A TOTAL PRESSURE REACTED OF 338 psi (2.78 Ah)
  - RATE CONSTANTS FOR H<sub>2</sub> LOSS: 4.9 AND 4.6 x 10<sup>-3</sup> hour<sup>-1</sup>
- SUBSEQUENT REVERSAL SHOWED AN INCREASE OF 1.7 Ah IN PRECHARGE (~60% of 2.78 Ah)

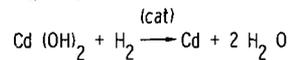


Figure 4-77

### Experimental Arrangement

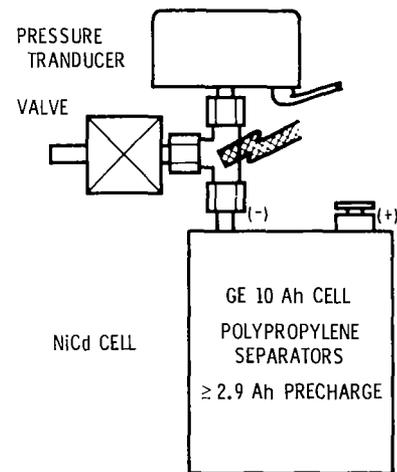


Figure 4-76

### Observations During Reversal and Kinetics of Loss of H<sub>2</sub> from Reversed, Open Circuit Ni Cd Cells

- PROCEDURE:
  - CHARGE AT C/10 FOR 16 hr (optional)
  - DISCHARGE AT C/2 (5.0 amp) TO 0 V (optional)
  - CHARGE AT C/5 FOR 1 hr
  - DISCHARGE AT C/5 INTO REVERSAL UNTIL DESIRED PRESSURE OR -0.5 V IS REACHED
  - OPEN CIRCUIT
- CONTINUOUSLY RECORD VOLTAGE AND PRESSURE
  - PRESSURES CORRECTED TO 24°C
- TEMPERATURES USED: 40, 32, 24, 22, 9.5°C

Figure 4-78

Voltage and Pressure During C/5 Reversal

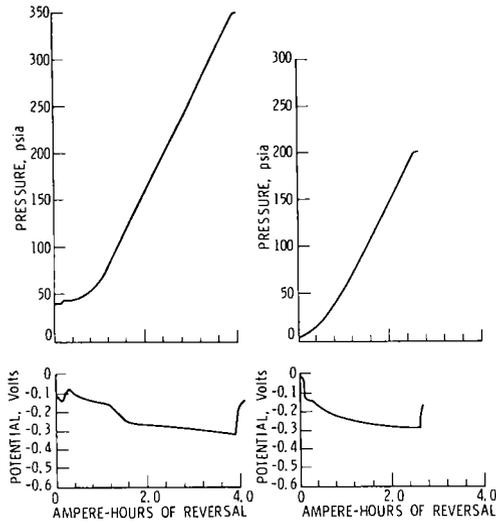


Figure 4-79

Summary of Data for Open Circuit Stand Experiments

EXP No.	TEMP °C	P <sub>0</sub> psia	CELL A CAPACITY Ah	(k) × 10 <sup>-3</sup> hr <sup>-1</sup>	P <sub>0</sub> psia	CELL B CAPACITY Ah	(k) × 10 <sup>-3</sup> hr <sup>-1</sup>
6	9.5	266	11.2	2.1	250	11.6	1.5
1	2.2	258	11.9	6.2	334	12.6	4.9
5	2.4	111	11.7	5.7	148	12.3	5.0
7	2.4	252	--	11.1	236	--	5.5
8	2.4	250	12.2	5.3	234	12.4	2.6
9	2.4	251	11.8	6.9	236	12.0	5.4
4	3.2	243	--	11.4	228	--	9.6
2	4.0	242	11.1	33.4	225	12.3	21.7
3	4.0	159	--	20.1	138	--	12.9
H <sub>2</sub> ADD'N	2.2	--	--	4.9			
				4.6			

Figure 4-81

Log P(H<sub>2</sub>) vs Time for H<sub>2</sub> Reaction Cell A, Experiment 5, 24°C

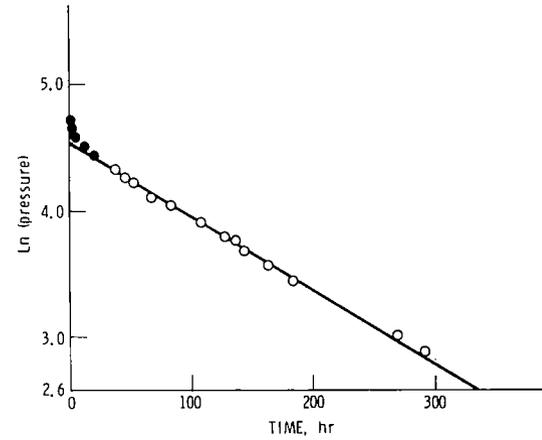


Figure 4-80

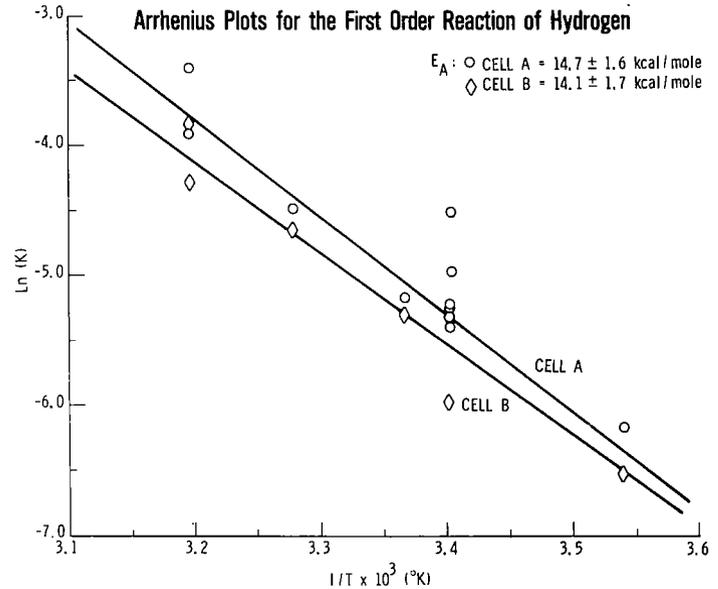


Figure 4-82

## Pressure and Voltage Behavior During Constant Low Rate Reversal After High Rate Reversal

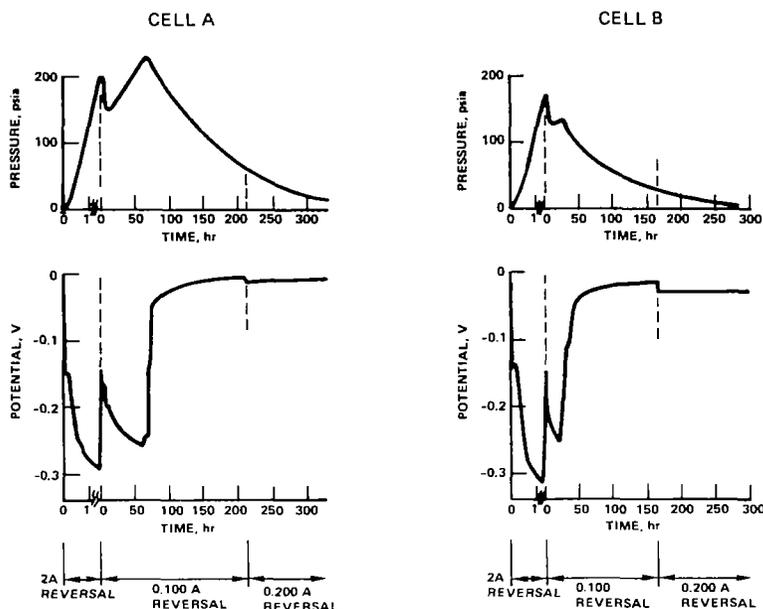


Figure 4-83

### Results of Low Rate Reversal Studies

- CONTINUOUS, LOW REVERSAL CURRENTS (C/50, C/100) EVENTUALLY RESULT IN OHMIC SHORTING IN THESE CELLS
  - NO SHORTING WAS OBSERVED DURING HIGH RATE REVERSALS
- RATE CONSTANTS ARE SIMILAR UNDER ALL CONDITIONS AT 24°C FOR H<sub>2</sub> DECREASE

	CELL A (K) x 10 <sup>-3</sup> hr <sup>-1</sup>	CELL B (K) x 10 <sup>-3</sup> hr <sup>-1</sup>
LOW RATE REVERSAL (after high rate reversal)	10.0	10.7
LOW RATE DISCHARGE AND REVERSAL (C/100)	6.4	4.7
OPEN CIRCUIT AFTER HIGH RATE REVERSAL	7.3 ± 2.7	4.6 ± 1.4

- THE OHMIC SHORT FORMED DURING LOW RATE REVERSAL IS REMOVED BY OPEN CIRCUIT STAND OR BY CHARGING (C/10)
  - NO ILL EFFECTS OF SHORTING OR REVERSAL HAVE BEEN DETECTED IN THE ELECTRICAL PERFORMANCE

Figure 4-84



## CELL SHORT CIRCUIT, PRESHORT SIGNATURE

C. Lurie  
TRW

(Figure 4-85)

TRW has been running ground test simulations of DSCS-3 missions for some time now. During the flight 7 simulation, several short-circuit events were observed.

In the process of our looking at what happened, we took a very, very close look at the cell level data preceding each of the short-circuit events. In the process of this investigation, we discovered that there was a voltage signature appearing anywhere from days to weeks prior to this short-circuit event. What I would like to discuss is what we saw and what we think it means.

(Figure 4-86)

It is necessary to describe this system just a bit. The ground test that we ran is a simulation of geosynchronous orbit cycling. It is the familiar 45 eclipses per season. We run real-time eclipses. There is no attempt to accelerate that part of the test. Mid-season maximum DOD is 40 percent, and that is at 72-minute discharge.

We reconditioned after each season. Reconditioning discharges into a 44-ohm load to a 1-volt per cell cutoff. The solstice period is accelerated to the extent that the 135 days is cut back to the time necessary for reconditioning only, which is approximately 1 to 2 weeks.

We have completed six seasons and the test is continuing. The test battery is a 22-cell battery with the indicated 12-ampere hour GE cells with nylon separator. The negatives are not teflonated.

(Figure 4-87)

The battery is mounted on a thermal electric baseplate. The battery baseplate interface is adjusted to give us a thermal profile equivalent to the actual orbital mission. The battery is hooked into the battery lab digital data acquisition system which gave us sufficient data on a continuing basis to perform this analysis.

The battery is switched between trickle charge and full charge based on temperature as indicated on the right. As the battery goes up, it switches down to trickle charge at about 76 degrees. On temperature fall it goes to approximately 70 degrees.

(Figure 4-88)

This rather busy looking curve is a summary of a typical mid-season profile showing battery voltage, battery current, and temperature.

This portion of the curve is the discharge. We come out of discharge, the temperature drops, and the voltage goes up. When the temperature drops sufficiently, we go into full charge. In full charge the temperature increases. While this is happening, the battery voltage goes up and reaches the voltage limit.

As we come off this because of temperature rise, the battery is about fully charged. It has taken about as much as it can. After this, everything you see is overcharge. We have what amounts to a series of overcharged pulses. This gives rise to what amounts to a battery voltage response to these current voltages, which looks very much like a series of square waves. And if you keep that in mind, that is what the signature turned out to be.

(Figure 4-89)

We saw a number of different types of short circuits. Hard shorts, of course, are very easy to define and see. The battery voltage goes to zero.

I don't want to, as part of this discussion, get into a discussion of what a soft short is, so we chose a simple working definition which I think is valid for what we have observed. Let me just say any time we saw anomalous voltage decrease that wasn't trivial, was greater than 100 millivolts, we called it a soft short. There should be a sense of time there. This usually occurred in minutes to hours, rather than hours to days.

Now, if you recall the voltage response to the current pulses for a nominal cell, it is about what this solid line looks like. The voltage ramps up. We have an initial square wave which is charging. We have a number of ensuing square waves which, in fact, are overcharge pulses.

However, in all instances the cells which exhibited hard or soft shorts, what we saw at some time prior to the short was something that looks like this dotted line. Where the voltage was depressed and coming into the charge region, we saw a feature of some kind at the beginning and a ramping up. In each of the subsequent overcharge pulses, instead of being squared, it ramped up. We defined our signature in terms of a degraded overall voltage, a ramping of the charge and discharge pulses and this feature which appeared at the beginning of this charge pulse.

(Figure 4-90)

Now, some specific data is information taken during cycle 24 of the third season. We plotted six different cell voltages in pairs to show the superposition of the data. In other words, the individual cells tracked one another. If they were nominal, they tracked very, very well. We didn't attempt to superimpose all six, because it wouldn't be readable.

You can see that one cell, cell number 14, is showing some very, very slight indication of ramping, and slightly depressed voltage.

(Figure 4-91)

Now moving to cycle 34 of the same season, in other words, ten 24-hour cycles later, three of these cells exhibit the signature as indicated, a generally depressed voltage feature at the beginning of the chart, falls, and this ramping.

I should point out during these 10 days battery help as we would normally judge it, based on the kind of information we would have from a battery in orbit, battery help would have been excellent. There would have been no indication that anything was wrong or about to be wrong, based on the normal battery telemetry. In fact, at this point the battery was still behaving fine, accomplishing its mission. We did have the signature.

(Figure 4-92)

At the end of that season, in other words, almost 2 weeks later during reconditioning, two of the cells which exhibited the signature dropped out of the reconditioning discharge very, very early. Cell number 14 and cell number 17 dropped out at about 2 and about 6 or 7 ampere-hours in. Cell number 19 was just included, as an example of a cell which did not exhibit a short-circuit signature.

(Figure 4-93)

If we move to cycle 24 of season 5, or approximately 100 days later, cell number 14 dropped out. Let me explain what we have here. We have plotted six cells, and we have displaced the scales so the data would be readable on the six cells.

Cell number 14 started out low but was remaining parallel to the remaining cells. At this point an inflection occurred. At this point the second inflection occurred, and we associate some physical process with the presence of the inflection.

Then, the cell dropped off fairly rapidly and, in fact, went into reverse, and reversed for about 1 ampere-hour or so. Then, again immediately prior to this reversal, battery health had been good. The only reason we would have expected something was wrong was the presence of the signature which persisted through this time.

(Figure 4-94)

So, what do we think the signature means? Probably the depressed voltage is some kind of a high impedance shorting that exists. What is interesting and perhaps a little difficult to explain is that it appears, whatever it is, to be stable, to be capable of being stable for long periods of time. In fact, that seems to be unpredictable. When we see the signature, the cell may go out in hours, or it may go out in weeks. But it is capable of being stable.

The ramping is probably the easiest part to explain. If there is this partial short you go into that pulse, charge pulse not fully charged so the voltage isn't going to jump up immediately, it is going to go up gradually.

That little feature that we saw at the beginning of the charge pulse is perhaps the most mysterious part. But it may suggest that the signature itself is charge dependent and that we are at the lowest state of charge. Whatever its manifestation, it behaves differently once the battery goes past its first stage of charge. But that is purely speculation.

Are there any applications of this possible? I think the question that has to precede that is, how general is the phenomenon? Will we be able to use it in other similar situations? That is something we are talking about.

If we can and if it is reasonably general, perhaps this could develop into short circuit early warning system if we had some microprocessor capability, an algorithm to sense the curve shape.

What we are doing at present is some extensive DPA autopsy work on these cells to try and correlate the degree of problem that we think we are having with physical observations during teardown analysis. We hope that will tell us a little bit more about what we are seeing.

## DISCUSSION

FORD: I couldn't tell from the back of the room, what is the rise time of the pulse?

LURIE: The rise time is rapid. I don't know.

FORD: What was the width of the pulse?

LURIE: This is a 24-hour charge.

So that's on the order of what? Half an hour? 45 minutes? That's a function of the thermal characteristics of the system.

LURIE: As soon as it heats up, it is going to drop off.

HENDEE: I find that very interesting. There are several other preshort signatures, though, that one could probably observe. It depends on whether it is a short on charge — there is that type which may give you problems. You may see that in your subsequent reconditioning.

Then, there may be the continuous type of short. I have seen signatures that start out with, when you are recharging your normal voltage peaking, and then decrease, you just start seeing, instead of going up to a nice peak and then levelling back off, it goes up and just keep smoothing out, smoothing out until you are just approaching it.

I have seen other ones starting to go up and then there's a clamp. I have seen cells on slow charge which I will have a plot of tomorrow on my presentation. But you do see an oscillation in the ampere per hour voltage. There are many of them.

SCHULMAN: Did you try to correlate in any particular cell, where you found a signature of a soft short with a test that is being used in battery acceptance testing, cell acceptance testing, that charge retention-type test which is supposed to indicate a short?

LURIE: What we did correlate with very successfully was capacity, voltage decay in a fully charged state.

We charged the battery up and let it sit for a period of 7 days. When we did a statistical analysis, we found that all the cells except two were very, very close, around the three sigma limit. Two cells dropped out of the three sigma limit, and the cell that was furthest away from the three sigma limit failed first. And the cell that was closer to the three sigma limit but out of it failed second. So we did get very, very good correlation with a more classical test.

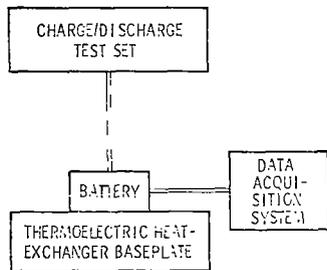
- SEVERAL CELL SHORT CIRCUIT EVENTS WERE OBSERVED DURING A GROUND TEST SIMULATION OF DSCS II F7 BATTERY OPERATIONS.
- CELL LEVEL DATA FOR THE PERIOD PRECEDING THE SHORT CIRCUIT EVENTS WAS INSPECTED FOR ANOMALIES.
- THE RESULTS OF THIS INVESTIGATION SUGGEST THAT CANDIDATE CELLS DEVELOP A CHARACTERISTIC SIGNATURE ANYWHERE FROM HOURS TO DAYS PRIOR TO A SHORTING EVENT.

- THE GROUND TEST IS A SIMULATION OF GEOSYNCHRONOUS ORBIT CYCLING.
  - 45 REAL-TIME ECLIPSES PER SEASON: MAXIMUM DOD = 40%.
  - RECONDITIONING AFTER EACH SEASON: BATTERY IS DISCHARGED INTO A 44 Ω LOAD TO A 1V/CELL CUTOFF.
  - THE SOLSTICE PERIOD IS SHORTENED TO THE TIME REQUIRED FOR RECONDITIONING AND RECHARGE ONLY.
- SIX SEASONS HAVE BEEN COMPLETED AND THE TEST IS CONTINUING.
- THE TEST BATTERY CONTAINS 22 GE 12 AH CELLS, P/N 42B012AB20 WITH NYLON SEPARATOR. NEGATIVE PLATES CONTAIN SILVER BUT ARE NOT TEFLONATED.

Figure 4-86

GEOSYNCHRONOUS ORBITAL SIMULATION

TEST CONFIGURATION



SSTS SWITCH POINTS

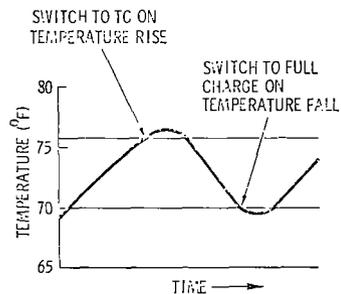
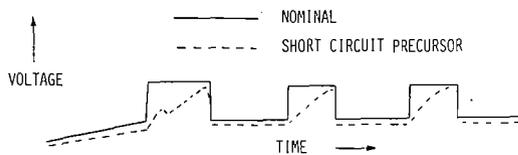


Figure 4-87

CELL SHORT CIRCUIT, PRESHORT SIGNATURE SHORT CIRCUIT EVENTS

- DESCRIPTION: HARD, SOFT, INTERMITTANT
- "SHORT" DEFINITION  
FOR PURPOSES OF THIS STUDY ANY ANOMALOUS VOLTAGE DECREASE GREATER THAN 100 mV WAS CONSIDERED TO BE EVIDENCE OF A SHORT.
- PRECURSOR OBSERVATION



- "SIGNATURE" DEFINITION
  - DEGRADED OVERALL VOLTAGE
  - "RAMPING" OF CHARGE AND DISCHARGE PULSES
  - "FEATURE" AT THE BEGINNING OF THE CHARGE PULSE

Figure 4-89

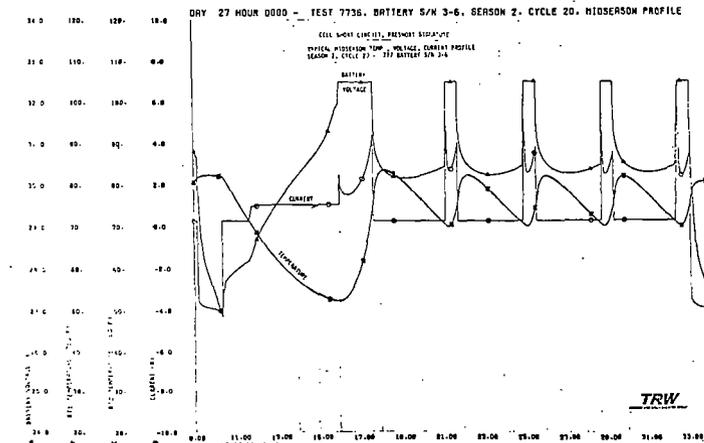


Figure 4-88

CELL SHORT CIRCUIT, PRESHORT SIGNATURE

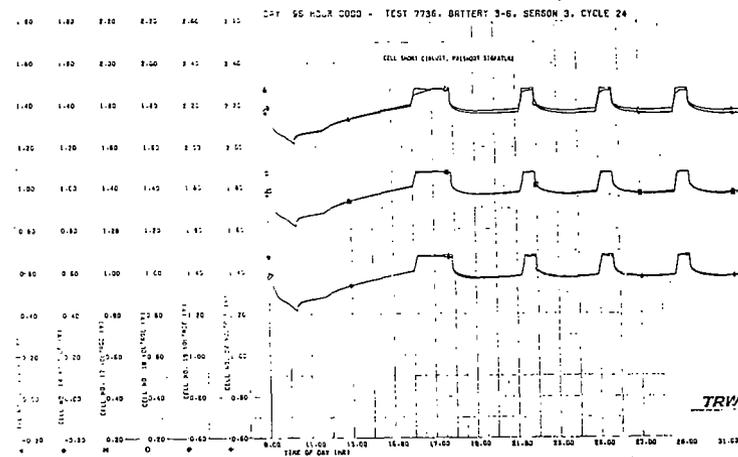


Figure 4-90

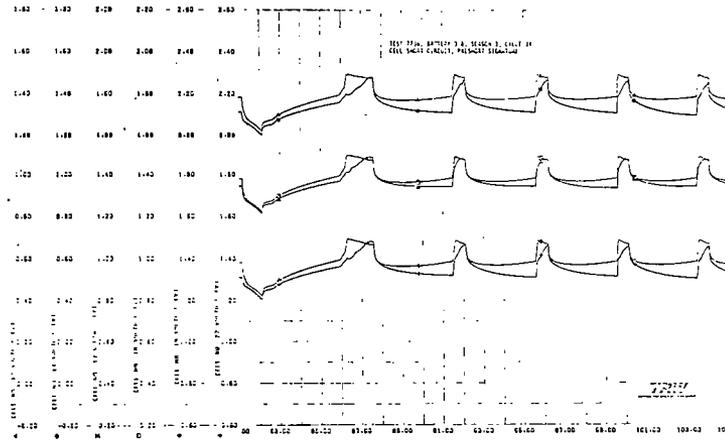


Figure 4-91

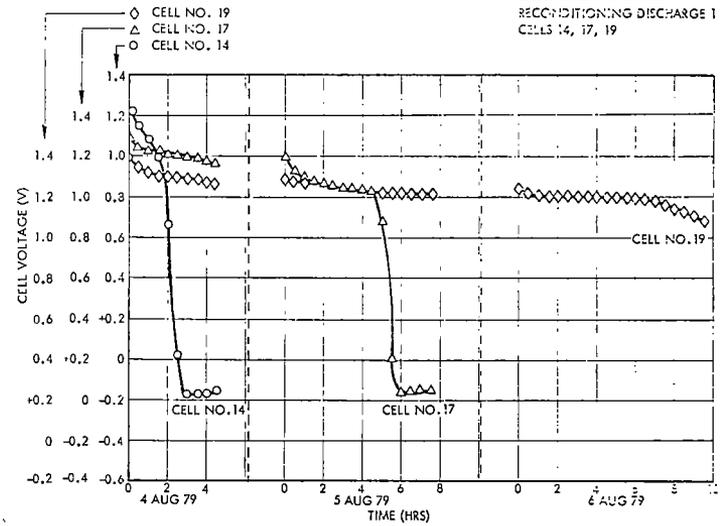


Figure 4-92

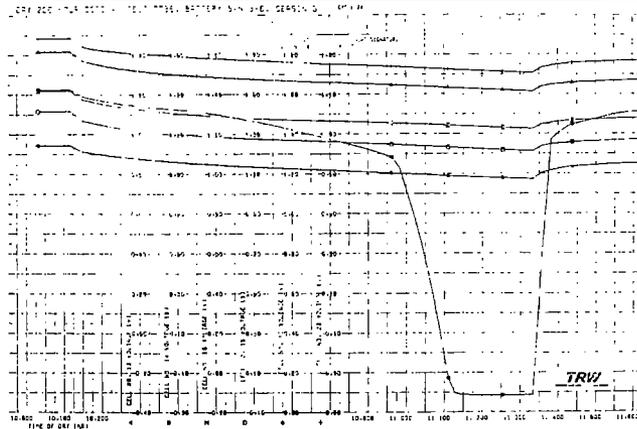


Figure 4-93

- PHYSICAL INTERPRETATION OF THE SIGNATURE
  - DEPRESSED VOLTAGE-----HIGH IMPEDANCE SHORTING PATH WHICH CAN BE STABLE FOR A PERIOD OF WEEKS.
  - "RAMPING"-----BATTERY IS PARTIALLY DISCHARGED AT THE BEGINNING OF THE PULSE.
  - ANOMALOUS CHARGE-----THE PHYSICAL SIGNIFICANCE IS NOT CLEAR AT PRESENT BUT IT MAY SUGGEST THAT THE NATURE OF THE SIGNATURE IS STATE OF CHARGE DEPENDENT.
- APPLICATIONS-----AS A SHORT CIRCUIT EARLY WARNING SYSTEM,
- WORK IN PROGRESS-----DPA TO CORRELATE TEARDOWN OBSERVATIONS WITH SIGNATURE/SHORTING EVENT HISTORY.

Figure 4-94



## POCKET NICKEL CADMIUM CELL AND BATTERY EVALUATION

J. Lear  
Martin Marietta

The pocket NiCad battery has been around for a long time, and I wish to thank Floyd and Jerry for permitting me to present this at this workshop. Since this is a workshop, it is nice to present it.

The reason why I would like to present this paper is that we were looking at a military application that required a battery, not an aerospace-type battery, but a NiCad battery for a military application. Nife Corporation of Lincoln, Rhode Island and Sweden, loaned us 22 cells to test.

Since there is such a small data base on this particular battery and it had never been tested in a military application, I thought it was an excellent opportunity to test it and to present some of the results that I got during this testing.

(Figure 4-95)

The purpose of the test was to evaluate the 129-ampere hour cell to characterize the cell under controlled conditions. One test is missing there. It was an open-circuit stand test which I will talk about on the next chart.

(Figure 4-96)

Again, Nife loaned us 22 cells of which five modules were monoblocks, five and six-cell monoblocks, and we divided them up into various tests. We had five of them on charge characterization, which later on we went into ampere-hour efficiency tests.

We put five on discharge characterization; we had five on open circuit stand, and there were six that just sat open circuit with nothing going on.

(Figure 4-97)

This is a little bit of a description of the cell. You can see it is a big hummer, not a small guy. It is 15 inches tall and weighs roughly 15 pounds. The resistance you will notice I have scratched out there. Nife was nice enough to give me some updated information. It is 1.1 milliohms.

(Figure 4-98)

We have 27-cubic foot test chambers at Martin Marietta. You can see that's a five-cell monoblock, and you can see how much space it takes up in the cube itself. The total 22-cell battery weighed 330 pounds. I don't expect you to run out and put it in a spacecraft.

(Figure 4-99)

This is a drawing that was put together by myself and an illustrator at Martin showing the way a pocket NiCad plate is designed, put together or manufactured. At the top is a roll of metal steel which is 0.1 millimeters thick. It runs through a punch press that has needles that punches on either side of the plate, and you come out with a form plate that has got holes all perforated through it.

Previously, the method was to punch holes on one side. But now they are punching holes on both sides which gives them 30 percent more area for the electrolyte to flow through the plate.

Little briquets are then placed within the stamped plates. As you can see here, the edges are folded over and they interweave. When the plate is all put together, they are a nice, solid mesh plate. Both the positive and negative plates are made this way.

(Figure 4-100)

You will notice that the manufacturer recommended voltage limits on the right-hand column. This data was generated after we had already got into our tests, well along into our tests, and we had made some assumptions along the way that terminate the voltages at the selected voltages there. And we charge the cells at various rates; 5, 10, 15, and 25 amperes constant current until either a voltage limit cutoff or a time cutoff.

You will see later on that under the minus 10 condition, I have made an error in selecting the voltages. I did not know what the voltage cutoff was or recommended. I had arbitrarily picked a number.

(Figure 4-101)

Here is the result. You will see at the plus 40- and plus 25-degree state during the charge categorization test, that for the 5, 10 through the 25, we did get roughly 140 to 150 ampere-hours of capacity out of the cells.

But in the minus 10 condition, because I had made an error in judgment of picking too low, we did not get full state of charge. It is not the problem with the battery but was a problem with me. So, I didn't have anything to base my judgment on, and I just went ahead and picked a number.

(Figure 4-102)

This is some of the typical charge characteristic curves that I have got. These charges represent the capacity that I took out on a previous charge at the various temperatures. In other

words, if you look at the 25-degree charge here, I took out roughly 130 ampere-hours of capacity out of the cell at the particular test, and that's what I put back in.

This is where I went into the gas evolution. You will notice I took out roughly 80 to 90 ampere-hours of capacity at that minus 10- and 40-degree test.

(Figure 4-103)

The discharge characterization is just a normal nice, smooth curve indicative of the nickel-cadmium system. I just wanted you to see what the curves looked like as I saw them during the tests.

(Figure 4-104)

Ampere-hours efficiency for the three charge conditions I was working with. It turned out I was operating somewhere between 55- and 95-percent ampere-hours efficiently through the charge characterization tests. It was a very excellent system for ground operations communications or terrestrial applications.

(Figure 4-105)

For open-circuit stand, we went actually 240 days, but I plotted out 200. We had six cells that we took. Periodically we would discharge them.

During the initial characterization test, we checked out the capacity, and we have got for the 22 cells, an average of 150.25 ampere-hours out of 129-ampere hour cells, which indicated we had like a 17-percent excess capacity above the nameplate capacity.

Again, the cells had never been tested to my knowledge, I don't think to Nife's knowledge, in this type of a regime. So they also were a little bit elated with some of the data that we got for them.

(Figure 4-106)

The five-cell was monoblock that I had for discharge characterization test. Nife and I do not see eye to eye on this (they are in the crowd, and they may expound on that later on), but when we did the characterization test, I left some of the cells sitting around in open-circuit charge. Five of the cells, (this particular monoblock), were low in electrolyte, and for some reason, the capacity was low when we went to test them. I do not have an explanation for it. Nife may offer some answer. I do not have an answer on that. I will let it go at that.

(Figure 4-107)

For terrestrial application, ground power communications, the system is excellent. It offers an excellent capacity over wide operating range and a large temperature range. Higher cutoff voltage

was required, as I showed you. I had picked the wrong number. Since then Nife has come out and has come up with a set of limits that we can work with in a military-type application. Reasonable ampere-hour efficiency is afforded with this system.

Through the open-circuit stand time, we have only lost 3 percent a month. I think we only went down like 25 percent in 200 days. That's my results.

#### DISCUSSION

VOICE: How large was the pocket?

LEAR: How large was the pocket? 129 ampere-hours.

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INTRODUCTION: TEST AND EVALUATION OF 129 Ahr POCKET PLATE  
NICKEL CADMIUM CELLS/BATTERY IN SUPPORT OF  
MILITARY APPLICATION.

OBJECTIVE: TO CHARACTERIZE THE ENERGY STORAGE SYSTEM UNDER  
CONTROLLED CONDITIONS.

SCOPE:

- o CHARGE CHARACTERIZATION
- o AMPERE HOUR EFFICIENCY
- o OPEN CIRCUIT STAND
- o DISCHARGE CHARACTERIZATION
- o CYCLE LIFE OPERATION

**MARTIN MARIETTA**

Figure 4-95

**TEST PROGRAM**

- o CONDITIONING
- o CHARGE CHARACTERIZATION
- o OPEN CIRCUIT STAND
- o CYCLE EFFICIENCY
- o DISCHARGE CHARACTERIZATION
- o CYCLE LIFE

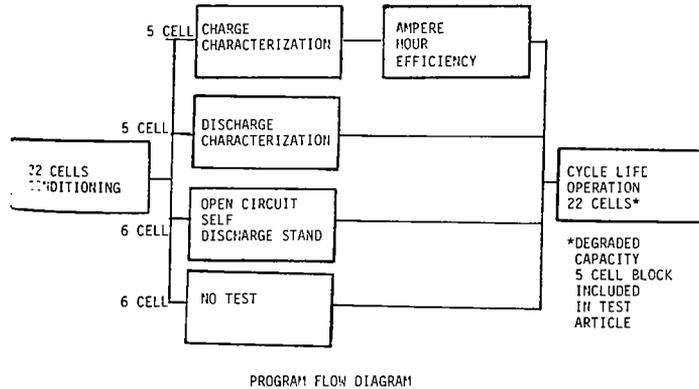


Figure 4-96

**TYPE L403 CELL DESCRIPTION**

HEIGHT 405 mm (15.9 in.)  
 WIDTH 194 mm (7.6 in.)  
 LENGTH 55 mm (2.2 in.)  
 WEIGHT 6.7 Kg (14.8 Lbs)  
 ELECTROLYTE VOLUME 2.0 L (0.53 g)  
 RESISTANCE 1.1 mΩ

\*FROM 100% S.O.C. TO 80% DISCHARGE @ 25°C

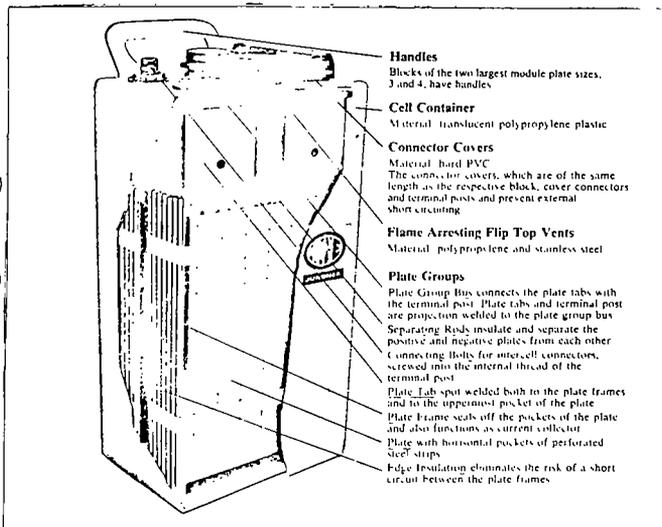


Figure 4-97

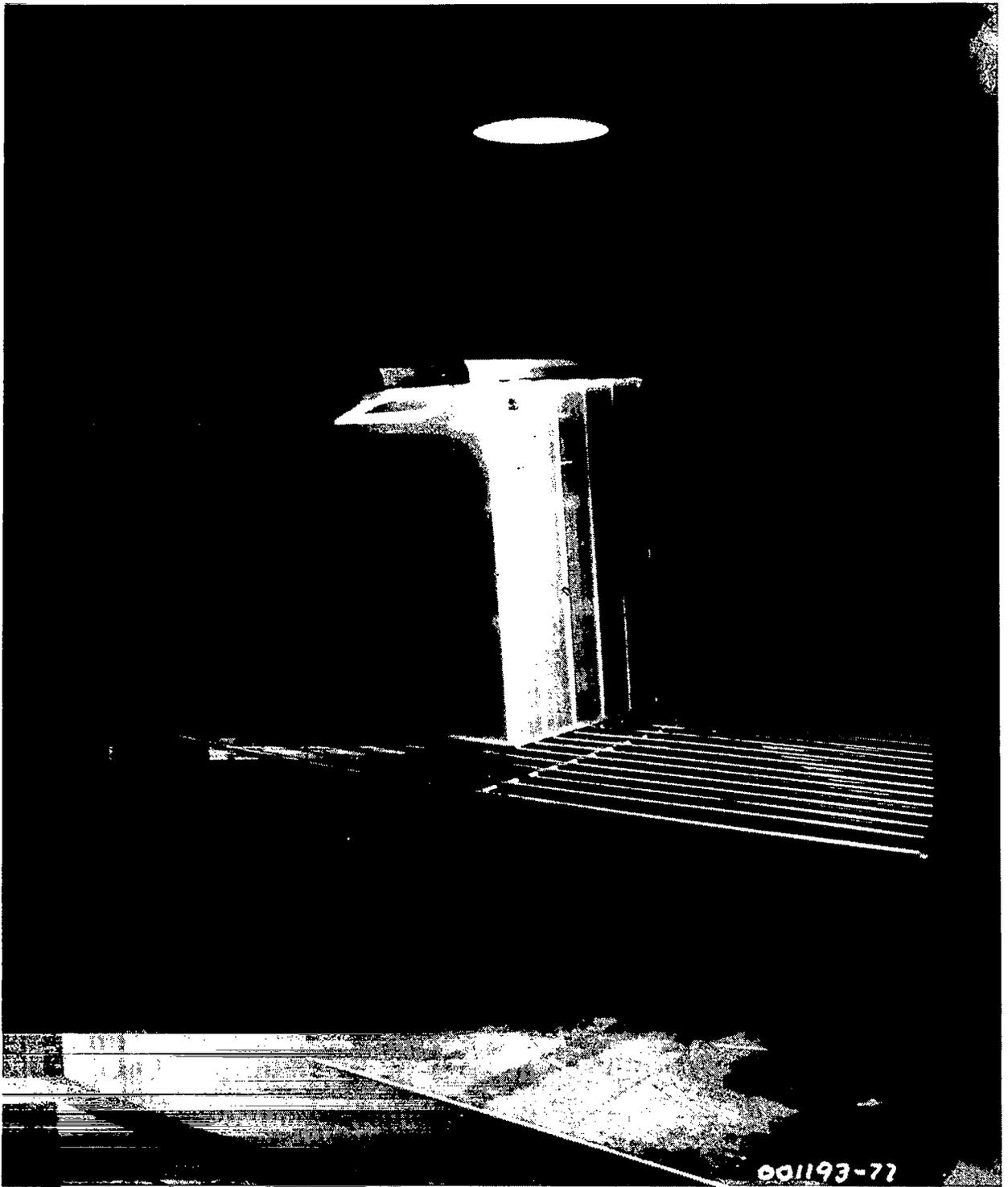


Figure 4-98

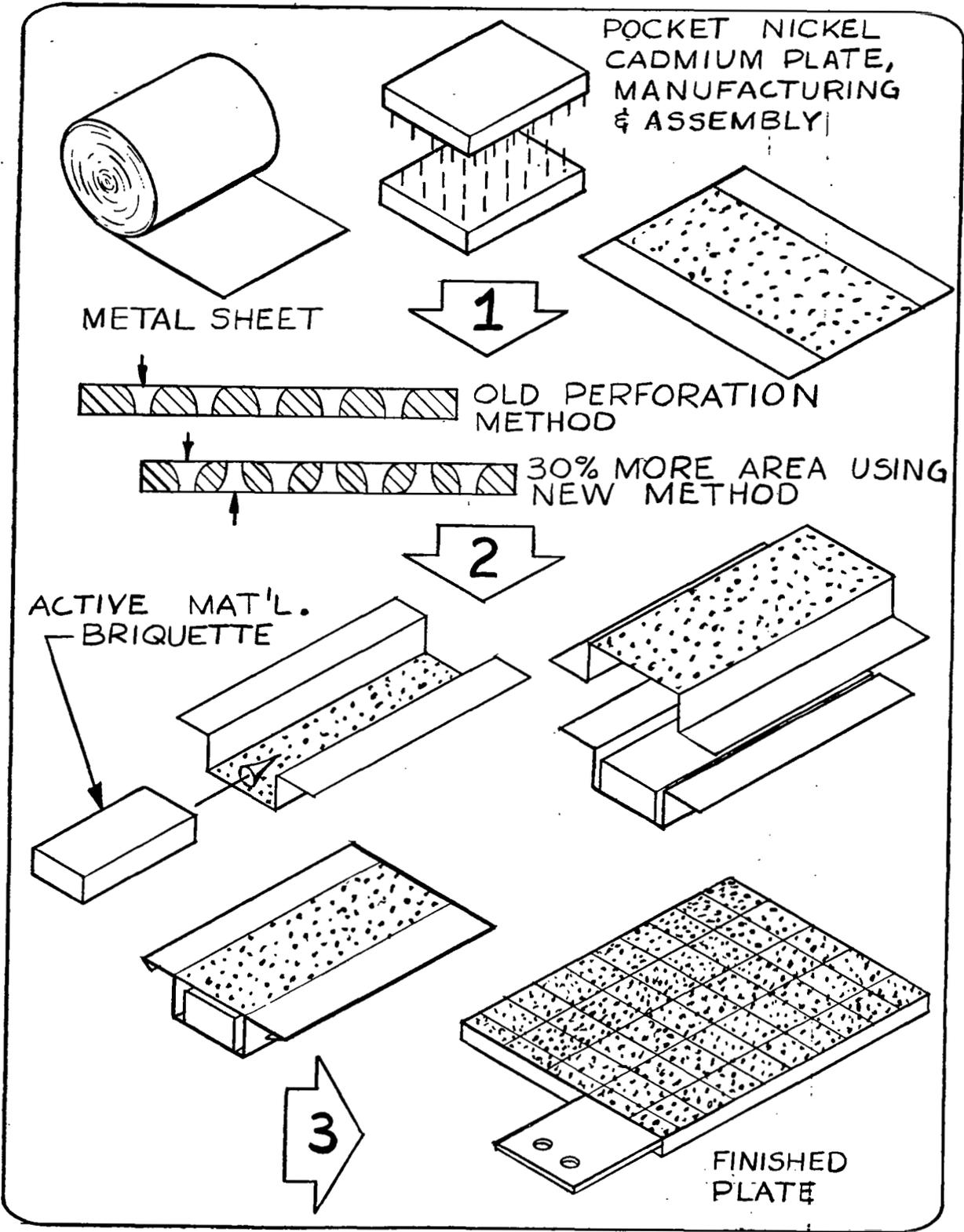


Figure 4-99

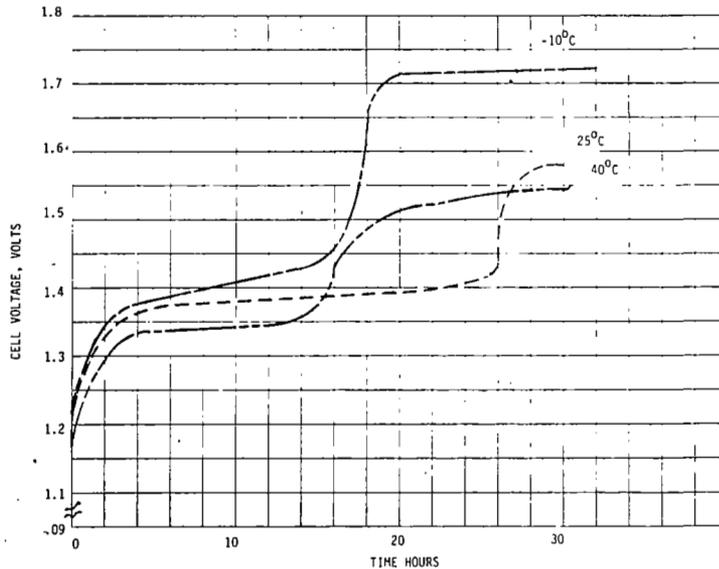
CHARGE CHARACTERIZATION MATRIX

CHARGE RATE (AMPERES)	TEMPERATURE C°	SELECTED VOLTAGE CUTOFF	MANUFACTURE RECOMMENDED CUTOFF
5	-10	1.72	1.82
5	25	1.63	1.66
5	40	1.58	1.61
10	-10	1.75	1.88
10	25	1.67	1.72
10	40	1.62	1.64
15	-10	1.76	1.89
15	25	1.70	1.74
15	40	1.65	1.66
25	-10	1.77	1.94
25	25	1.74	1.78
25	40	1.70	1.70

ALL DISCHARGES CONDUCTED AT A CONSTANT 10 AMPERE RATE

MARTIN MARIETTA

Figure 4-100



CONSTANT CURRENT CHARGE CURVES AT 5 AMPERE RATE AS A FUNCTION OF TEMPERATURE

Figure 4-102

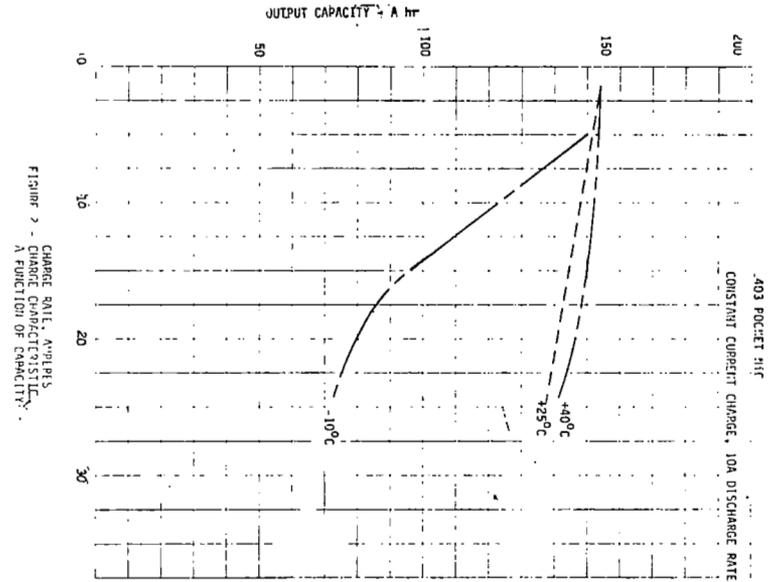
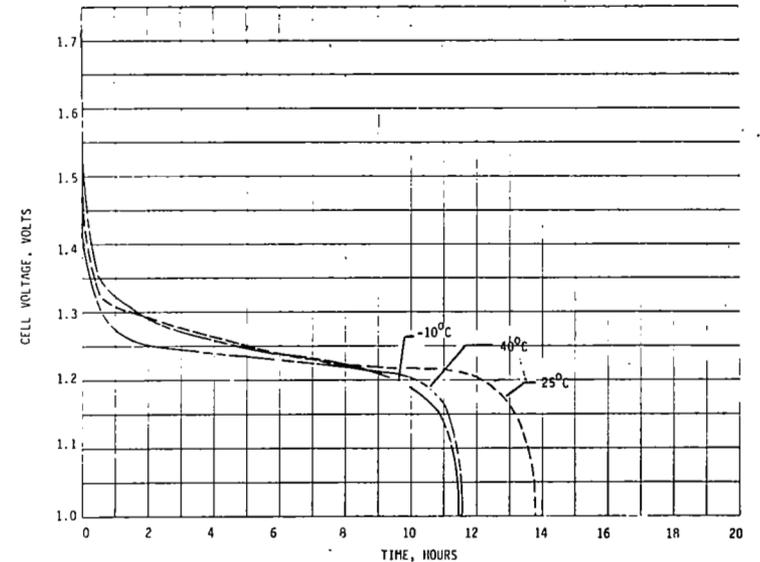


FIGURE 2 - CHARGE RATE, AMPERES, A FUNCTION OF CAPACITY.

Figure 4-101



CONSTANT CURRENT DISCHARGE CURVE AT 10 AMPERE RATE AS A FUNCTION OF TEMPERATURE TO 1.0 VDC

Figure 4-103

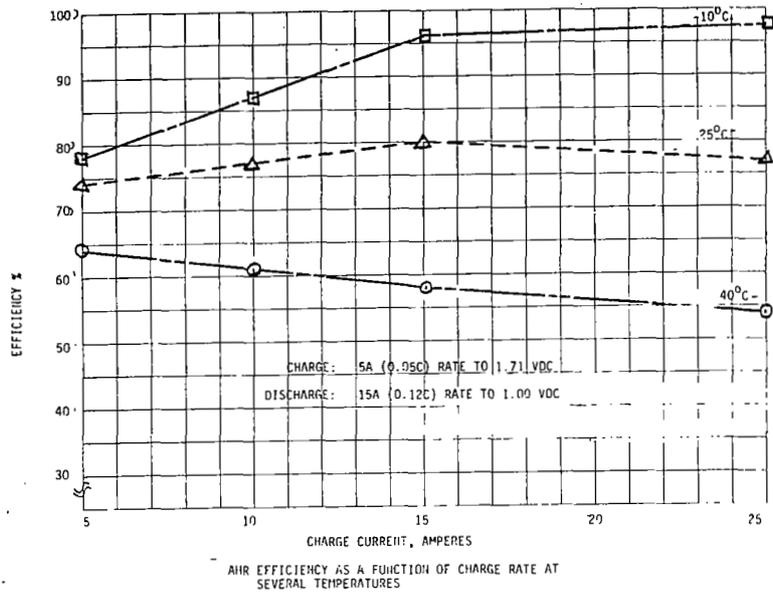


Figure 4-104

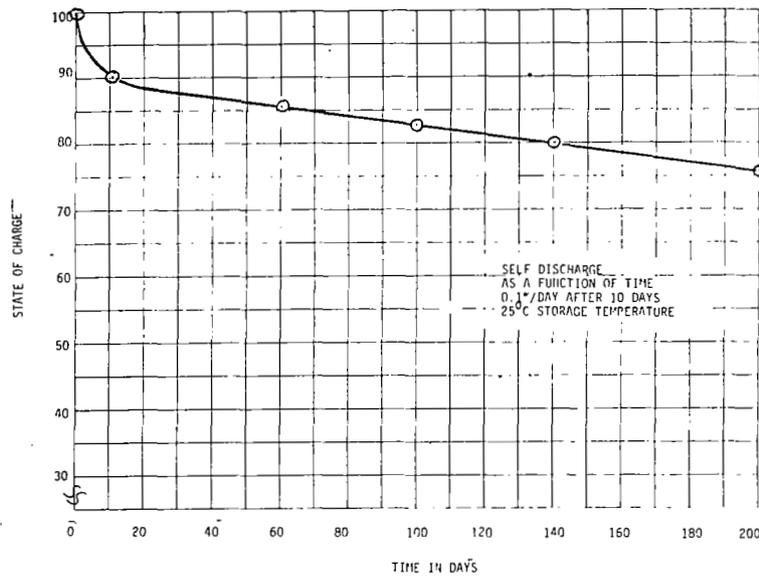


Figure 4-105

## DISCHARGE CHARACTERIZATION AND CYCLE LIFE TESTS

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- o 5 CELL BLOCK DESIGNATED FOR THE DISCHARGE CHARACTERIZATION TEST SUFFERED AN UNEXPLAINED ELECTROLYTE LOSS DURING 180 DAY OPEN CIRCUIT STORAGE PERIOD.
- o SUBSEQUENT CYCLING AFTER RESTORING ELECTROLYTE TO SPECIFIED LEVEL SHOWED A PERMANENT CAPACITY LOSS OF APPROXIMATELY 40%.
- o RESULTS OF SUBSEQUENT CHARACTERIZATION AND CYCLE LIFE TESTING ARE NOT CHARACTERISTIC OF NORMAL CELLS.

CONCLUSIONS:

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- o CELLS DELIVERED EXCELLENT CAPACITY AT 25<sup>0</sup>C AND 40<sup>0</sup>C.
- o HIGHER CUTOFF VOLTAGE REQUIRED AT -10<sup>0</sup>C AT CHARGE RATES IN EXCESS OF 5 AMPS.
- o REASONABLE AMPERE-HOUR EFFICIENCIES ARE ACHIEVABLE UNDER PROPER CHARGE CONDITIONS.
- o CELLS EXHIBIT GOOD CHARGE RETENTION CHARACTERISTICS (APPROXIMATELY 3% LOSS PER MONTH AT 25<sup>0</sup>C).
- o ELECTROLYTE MANAGEMENT REQUIRED TO PREVENT CAPACITY LOSS.

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**MARTIN MARIETTA**

Figure 4-107

SESSION V

CELL ANALYSIS AND DESIGN

F. Betz, Chairman  
Naval Research Laboratory



## NWSC NICKEL CADMIUM SPACECRAFT CELL ACCELERATED LIFE TEST PROGRAM DATA ANALYSIS

J. Lander  
AF APL

This topic will deal with the accelerated life test program which is being conducted experimentally at the Naval Weapons Support Center, Crane, Indiana, and we will talk about analysis and accelerated life testing.

One of the objectives of the program was to learn how to do accelerated testing to enable projection to ultimate life under spacecraft usage conditions. The program is essentially complete now in terms of affording the data for analysis to leading to a proposed accelerated life test scheme of affording the data for analysis to accomplish this particular objective. An analysis of the data leading to a proposed accelerated life test scheme is the subject of this paper. And I say "a proposed scheme" because I am sure the data can be worked over in at least several different ways.

(Figure 5-1)

This test plan and its rationale have been presented in detail in reference 1. That's the recent NWSC report. On this program five stress factors were selected for evaluation; DOD, temperature, amount of recharge, discharge and charge rates.

In addition, three cell internal design variables were investigated. These showed low or no effects on cycle life except perhaps in the very extremes, and moreover, they have no effect on accelerated life test design, so they won't be treated here.

(Figure 5-2)

In references 1 and 2, that's the Crane report I mentioned, and also one of mine, there are complete tables of data showing the individual cycle life values for each cell of the five-cell packs, and the stress and design factor conditions.

The data for factorial design prior to the program are shown as averages for several sets of DOD T and percent R combinations. Percent R is recharge in this table. These data have had early-failing cells eliminated from the calculated averages. I don't think we have to dwell on this table at any particular length because I am going to show you plots and tables of condensed data which come out of this.

(Figure 5-3)

Let's talk about the early failures for a moment. An analysis was made of the failure data which showed that there were 15 percent early failures in the fractional factorial experiment, and 29 percent in the star point experiment due to early high pressure.

A chemical analysis showed this to be due to the accumulation of hydrogen. The data showed it was associated with high-overcharge rates and large amounts of overcharge. It is my feeling – I think it is a little bit more than a feeling – that this result was actually induced by the constant current charge procedure which was employed for the test to simplify handling of charge rate and amount of overcharge variables both equipmentwise and data analysiswise.

In retrospect, I think it is obvious that some of this was bound to happen. When the reserve cadmium hydroxide is used up due to positive plaque corrosion and separator degradation, hydrogen has to be produced at the negative plate on overcharge. For high rates of overcharge and large amounts of overcharge, the oxygen recombination rate couldn't handle it at the surface of the negative plate, and when hydrogen gets into the head space it is difficult to recombine.

We had a program in our laboratory and also an accelerated life test program. We also chose the constant current charge procedure.

When high pressures occurred, the charge mode was changed to a modified constant potential. The pressures came down and the cells failed thousands of cycles later due to other causes.

Now, on the NWSC test program, pressure failures also occurred at about the same number of cycles as capacity failures. When this happened, these were counted in the group average which I showed you on the previous table.

Early failures due to internal cell shorting and low capacity amounted to about three percent of the large number of cells that were cycled on this program.

(Figure 5-4)

As early as 1973, a theoretical equation had been derived for cycle life as a function of percent DOD and temperature, which predicted cycle life to be a linear function of the expression shown on this graph.

Now the star point experiment, part of the Crane program, provided the first opportunity to check this particular function. It provided data at three-percent DOD values at 40° C. This data was shown to be linear, and moreover the line passed through the origin if percent DOD was based on the actual capacity of 7.4 ampere-hours rather than the nominal six-ampere hour capacity.

This provided for a point on the curve. The data will be shown later.

This result was one of the more important ones to come out of the star point experiment.

(Figure 5-5)

Now let's look at the effect of percent recharge.

Inspection of the data on the previous table shows that percent recharge has a definite effect on life. The high value, 200 percent, results in shortening life. This might have been expected if failure by loss in capacity is life limiting because corrosion of the positive plaque material and separator degradation both proceed during overcharge, especially at the higher temperature. Also, the greater the depth of discharge, the more the amount of overcharge. So that you have those factors working.

(Figure 5-6)

The average cycle-life values as a function of percent recharge from Table II are shown in Table III together with their reciprocals.

We have used the reciprocal life as a function of temperature to good advantage in data analysis on other programs.

(Figure 5-7)

The reciprocals are plotted as a function of temperature in this figure. The effect appears to be nonlinear and the plot indicates that by the time temperature becomes as low as 20° C, the effect of percent recharge might very well disappear. This will be an important result when temperature effect is considered later.

(Figure 5-8)

Let's look at charge-discharge rate combinations. Now we are going to treat these as combinations, not as individual effects. In this table, the averages across all groups shown in Table II data are given for the charge-discharge rate combinations: 4C, 2C, C, C/2, 4C, C/2 and C, 2C. The data shows that there is no essential difference among the combinations except for 4C, 2C, which yield appreciably higher cycle volume.

(Figure 5-9)

In this figure, the 4C, 2C averages are plotted as a parameter in a graph of cycle life versus temperature.

The averages of all the other combinations are lumped together at salient points on the basis of the Table IV data which showed that there are essentially no differences among the other combinations.

Also shown is data from the star point experiment for the 2C, C combination which is interpolated from Figure 5-11. Clearly this combination belongs not with the 4C, 2C combination but with the others, all the others.

The data are limited to the 140-percent recharge groups.

It is clear that the 4C, 2C combination results in high values of cycle life, while the other combinations result in values which are essentially equivalent. The conclusion is that the high-rate combinations of discharge-charge are not effective in accelerating failures. Consequently, they are of no value in accelerated test design.

This conclusion had been reached earlier, as long ago as 1973, on another program where the rate differences, however, were not so widespread.

In actual space application, nothing like a 4C, 2C combination was possible, even in orbits as low as 90 minutes. So, in considering the temperature effect a little bit later, the 4C, 2C data will be eliminated.

Now, the fact that the 2C, C combination does not give different results compared to the others, except for 4C, 2C, is a valuable bit of information and will be used later in accelerated test design.

Now let's look at the temperature and percent DOD combination.

(Figure 5-10)

For this analysis, the 200-percent recharge data and the 4C, 2C data will not be used.

In this figure, cycle life is plotted against the percent DOD which we showed earlier, with temperature as the parameter. And where 100-percent DOD is based on the actual capacity of 7.4 ampere-hours.

The star point and the fractional factorial experimental data are shown. Linearity of the star point data is clear. Convergence of the curves for the different temperatures at the origin results is to be expected.

(Figure 5-11)

The star point data is all for the 2C, C rate combination; however, as we showed earlier, its use is justified.

In preparation of working graphs for data analysis, it had been shown that the 200-percent recharge data also show convergence near the origin. On this basis, it seems reasonably well established that the function of percent DOD is that which we have used for the abscissa, and it remains now only to describe the temperature effect.

In the original derivation of the theoretical equation for the cycle life versus percent DOD and temperature, which will be presented a little later, it was considered that the degradation processes might double in rate per  $10^{\circ}$  C increment as temperature increases.

In this figure it is shown that cycle life more than doubles in the intervals 50 to 40. The 40 to 30 difference is 2.54 times the 50 to 40 difference.

In a previous treatment of the incomplete data it was indicated that cycle life might almost be trebling for 10° C increments as temperature comes down.

Now, at this time we have one cell group, which is No. 86, nearing completion of its test life. It is being cycled at 20° C, 40-percent DOD, and 105-percent recharge. Its average life can be estimated now, it has had three cell failures, to be in the neighborhood of 22,000 to 23,000 cycles. This gives us a fourth point on the cycle-life temperature curve for 40-percent DOD.

While the percent recharge for this group, that is 86, is 105 percent and not 140 as for the other 40-percent DOD data points, the previous figure which showed conversion of the reciprocal of the percent discharge data indicated at 20 degrees, differences in percent recharge may vanish. If so, we can make a plot of the temperature data as shown in this figure.

(Figure 5-12)

For the moment, let us consider only the actual data. That is group 86 in the figure. Then there is the fractional factorial data and the star point data. We will talk about the rest of the curve a little bit later.

(Figure 5-13)

Now, if the temperature effect were allowed to treble, then cycle life would be expressed as a functional table as shown in this vugraph.

(Figure 5-14)

The table in Figure 5-13 yields this table, and here we have the expression  $-(T-50)/10$  showing values of 1, 2, 3, 4 for those temperatures. The cycle life for trebling as shown in the previous figure will give us these values of cycle life for those temperatures.

Now this table leads to this equation for cycle life as a function of percent DOD and temperatures. For X and A we have the values shown.

The values of cycle life for 40-percent DOD calculated from the previous equation are plotted. That's this X value which comes from the empirical equation just shown.

This really isn't a bad fit considering that the cycle-life averages have about a plus or minus 10 percent average deviation.

While based on the data of Figure 5-5 for the effect of percent recharge – where we showed the reciprocal with the conversion – it may be satisfactory to draw the curve of this figure, as

representative of the temperature situation for 140-percent recharge. But it would not be correct for 105-percent recharge, which is what that data point is. That's a condition for that data point.

This is because the lower amounts of recharge result in higher cycle life at the higher temperatures as shown in Table II data.

To complicate this situation even further, it is probable, as temperature increases, that 105-percent recharge would be insufficient to maintain capacity. On the test in our laboratories, 110-percent recharge was insufficient at 43° C, but 120 percent was sufficient. So if we used 120 percent rather than 140 percent, the resulting curve would look something like that dashed line curve providing we get convergence at 20° C for the percent recharge function.

Even the dashed line curve would yield a pretty good fit to the empirical equation, which we showed, with modest changes in the constant 3, A, and X.

The temperature curve is shown with a dotted continuation which plunges towards zero-cycle life around 60 degrees. This is on the basis that star point data show this cell design to be incapable of cycling at 60° C, 60-percent DOD, and 140-percent recharge.

(Figure 5-15)

We can use the equation to predict cycle-life values through the three remaining cell packs which are all cycling at 105-percent recharge as shown in this table.

The conditions are 0 and 40 degrees temperature to 40 percent depth; 20 and 20, and 0 and 20. And these values of cycle life result from the equation.

The value of 50,000 cycles for pack 84N seems to be reasonable enough; however, the other two results represent a very high extrapolation of the data. We have no idea of the validity of such a projection on the low temperature end. Moreover, whether it is realistic or not, we are striving for ten-year life in orbit now, with the best break on DOD and temperature that we can get.

If we talk about a 90-minute orbit, only 58,400 cycles are required for a 10-year life. So, speculation about the two zero-degree values on that table seems rather idle.

It appears that a 10-year life in such an orbit could be achieved with this cell design for these combinations of temperature and percent DOD, where percent DOD now is based on a nominal value of six-ampere hours capacity.

This says, for a goal of 10-year life, the usable energy could be doubled by controlling temperatures at 10 degrees rather than 20. Operation at temperatures only slightly over 20 degrees will result in large increases in battery weight.

On the face of it, the design could be operated at 70-percent DOD nominal by increasing temperature to zero. And this would give us a factor of about three times weight reduction.

However, reliability of the empirical equation is involved as well as reduced energy availability at the lower temperatures. Change of failure-mode is a possibility also, perhaps resulting in earlier than predicted failures; especially lowered rates of oxygen recombination.

Now let's look at accelerated test design.

(Figure 5-16)

We have talked about a low earth orbit, specifically in 90 minutes.

With the failure of the discharge-charge rate combinations as failure-accelerating vehicles, we are left with percent DOD, temperature, and percent recharge as variables which we can experiment with through design or accelerated testing.

A percent DOD and temperature have been used commonly in the past. There is no doubt that large amounts of overcharge, that's percent recharge, in combination with high temperatures and percent DOD, accelerates failure but in a nonlinear fashion, even perhaps with the effect disappearing at about 20° C.

Now, with both temperature and percent recharge being highly nonlinear, it seems best not to try to work them both into test design, aside from the probability that we don't have enough information about the percent recharge variable to enable adequate treatment.

While use of the rate combinations did not work out, at least it told us that we could go as high as the 2C, C rate combination. This will enable achievement of time acceleration on testing. We must, however, eliminate premature hydrogen pressure failures. This is to be done by going to modified constant potential charging where voltage is limited to 1.53 volts or less.

Now, let's talk about the 90-minute orbit, and discuss the 30-minute discharge, and 60-minute charge in terms of 100-percent DOD based on the actual ampere-hour-cell yield. Now obviously for the 100-percent DOD situation on a 30-minute discharge, the discharge rate would be 2C, and for 50 percent DOD it would be C.

On a constant potential charge mode, the charge rate for a nominal six-ampere hour cell would start around 2C and taper to values of about C/7 during orbit charge.

On the basis of our tests at AFAPL the 110-percent recharge is adequate at 27° C and 120 is adequate at 43° C.

In service we want to achieve a 10-year life or a 58,000 plus cycles. For a test time acceleration factor of 10X, that is one year, we would be limited to 5900 test cycles if we were constrained to use the 90-minute cycle.

(Figure 5-17)

We show representative data for the GE cell design, which we are dealing with here, assuming that our empirical equation holds under all the temperature, and depth-of-discharge conditions shown.

Let's look at the 50-percent DOD which is 1.0 on the abscissa. Using a 90-minute cycle and a C, C/2 rate combination, testing would be constrained on the basis of 5900 cycles to a temperature of no lower than slightly under 30° C.

However, if we can use the 2C, C rate combination allowed by our analysis, the cycle duration would be halved by 45 minutes allowing 10,700 cycles per year. This allows testing at 20° C and a spread of 20° to 40° C gives an adequate range for extrapolation of time or zero or whatever.

At the same time, using a temperature of 30° C, 23 can go as low as 30-percent DOD. We want to do this to check out linearity of the percent DOD function on this cell design, or whatever.

Now this scheme would require a minimum of five cell groups and one-year test time to establish the 10-year service life at 30-percent DOD and 10° C. We probably would be right about in there.

We probably can achieve much faster acceleration without sacrificing prediction reliability by rendering extrapolations unduly formed or by forcing into higher discharge-charge rate combinations leading, perhaps, to spuriously high-cycle life values.

(Figure 5-18)

To summarize, the conditions for accelerating testing could be as follows for a 10X acceleration factor for demonstration of a 10-year life on a 90-minute orbit.

We used the CP recharge mode. We would have five cell packs minimum. We probably ought to use five cells as just a minimum per pack. Temperatures to be used would be 20°, 30°, and 40° C, percent DOD of 50, 40, 30 based on actual capacity. Using a 120-percent recharge to accommodate this 40° C temperature, and a 45-minute cycle we would use 2C discharge rate and a CP recharge mode.

Now I'd like to talk about the theoretical equation.

(Figure 5-19)

Originally in 1973, we derived a theoretical equation for cycle life where  $m$  is descriptive of the degradation rate,  $n$  is a number which is descriptive of the temperature effect on the degradation rate, and if the degradation rate doubles, the  $n$  equals 2.

You can think about it doubling on the basis of the old chemical rule of thumb that chemical reaction rates double for each 10° C rise in temperature.

(Figure 5-20)

In this last figure we have plotted the data for the empirical equation from the previous graph and superimposed on it data calculated from the theoretical equation for m and n combinations of 0.01, 2.1, 0.09 and 2.1. These are shown as gaps in the equation.

The empirical equation is shown as circles. The theoretical equation for these two sets of common measurements is shown as X's and squares.

Inasmuch as we have no data yet for 10° C, that 50° C point for the actual data is not too helpful in describing what cycle life will be at the lower temperatures. This is true because in going from 50 to 40 we are not beginning to feel the full upsweep of that curve.

We submit that the theoretical equation with m equal to 0.09 to 0.1 and n equal to 2.1 is not a bad fit to this situation. Therefore, the original theoretical equation may give us a good foundation for more intensive development relating theory more intimately to the degradation process.

I think it can be said that this program not only was the most comprehensive accelerated life test program ever undertaken for NiCad spacecraft cells, but it has been very instructive. In retrospect, experimental design might have been modified. That is, we could have used the CP recharge mode rather than constant current and eliminated the very large amounts of overcharge. But it is a very good program to have behind us.

## DISCUSSION

HESS: Can you give us the report number of that NWSC report you mentioned?

LANDER: I am sure you can get it from Harry Brown from NWSC who is here, and maybe if you are lucky, he will have the report to give you.

ROGERS: I am wondering whether the number of cycles, in a 45-minute cycle at the higher rates, compared to a 90-minute cycle at equivalent lower rates, would give you the same length of time in cycle life?

LANDERS: The answer to that is no, it will give you half the time and that's why we can get as many as 10,000 plus cycles in a year instead of only 5900 cycles in a year.

ROGERS: I think what I was driving at was the life of the cell would be 5000 cycles in the 90-minute orbit, or 10,000 in a 45-minute with the same DOD. Would it be the same elapsed time period?

LANDERS: It should be the same according to this data analysis, if you want to believe the data analysis.

ROGERS: The same number of cycles.

LANDERS: Right.

SEITZ: Would this empirical equation be generalized to commercial nickel cadmium batteries, particularly in smaller sizes, rather than portable type?

LANDERS: What we would hope is that in the event that we wanted to test a new design or a different design, for example, the general shape of the equation would hold. But the constants in the equation would change on the basis of whatever the design might be.

TEST VARIABLES

ENVIRONMENTAL

1. DEPTH-OF-DISCHARGE (DoD)
2. TEMPERATURE (T)
3. AMOUNT OF RECHARGE (% R)
4. DISCHARGE RATE (MULTIPLES OF C)
5. CHARGE RATE (MULTIPLES OF C)  
DISCHG.-CHG.-CONSTANT CURRENT

DESIGN

1. AMOUNT OF ELECTROLYTE
2. CONCENTRATION OF ELECTROLYTE
3. AMOUNT OF NEGATIVE PRECHARGE

DESIGN FACTORS: NOT CONCERNED IN ACCELERATED TEST DESIGN

Figure 5-1

Table 1  
Life Cycle Data, Factorial Design Experiment

30°C				50°C			
40% DOD		80% DOD		40% DOD		80% DOD	
140%R	200%R	140%R	200%R	140%R	200%R	140%R	200%R
10,600 (1)	10,800+ (5)	3010 (7)	1630 (3)	4200 (8)	3260 (4)	930 (2)	720 (6)
15,500 (9)	11,500 (13)	2970 (15)	2200 (11)	5360 (16)	2040 (12)	1320 (17)	450 (21)
8440 (18)	3060 (22)	2860 (32)	2270 (28)	4610 (23)	2700 (19)	1900 (24)	550 (40)
12,400 (20)	5600 (30)	1320 (36)	2060 (33)	4620 (31)	2580 (27)	2510 (44)	750 (48)
11,600 (26)	7300 (39)	1290 (37)	670 (41)	6520 (38)	3100 (34)	1560 (59)	400 (55)
4700 (35)	7540 (47)	1700 (45)	1700 (50)	3110 (46)	860 (42)		1030 (63)
10,200 (43)	4930 (56)	1640 (54)	1670 (58)	5950 (53)	3350 (49)		
9720 (52)	6340 (64)	2840 (62)		2350 (61)	2680 (57)		
8410 (60)							
10,200±20%	7200±29%	2200±33%	1900±23%	4600±22%	2600±21%	1620±27%	650±18%

numbers in ( ) = cell group numbers.

Figure 5-2

EARLY FAILURES

- DUE TO HIGH HYDROGEN PRESSURES
- ASSOCIATED WITH HIGH ~~DISCHARGE~~-CHARGE RATES AND LARGE AMOUNTS OF OVERCHARGE
- INDUCED BY CONSTANT CURRENT CHARGE MODE
- ACCOUNTED FOR 15% OF FRACTIONAL FACTORIAL AND 29% OF STAR POINT EXPERIMENTS
- CULLED FROM DATA AVERAGES

Figure 5-3

% DoD FUNCTION

CYCLE LIFE  
LINEAR WITH

$$\frac{100 - \% \text{ DoD}}{\% \text{ DoD}}$$

AS PREDICTED IN 1973

Figure 5-4

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TABLE III

THE % RECHARGE EFFECT

EFFECT OF % RECHARGE	TEST CONDITION			AVERAGE LIFE	1/AVG LIFE (x10 <sup>4</sup> )
	T°C	% DOD	% R		
● LARGE AMOUNTS ACCELERATE FAILURE ESPECIALLY FOR HIGH DoD's, T's	30	40	140	10,200	1.0
	30	40	200	7,200	1.4
● NON LINEAR - EFFECT COULD VANISH AT T's BELOW ABOUT 20°C	30	80	140	2,200	4.5
	30	80	200	1,900	5.3
	50	40	140	4,600	2.2
	50	40	200	2,600	3.9
	50	80	140	1,600	6.2
	50	80	200	650	15.0

Figure 5-5

Figure 5-6

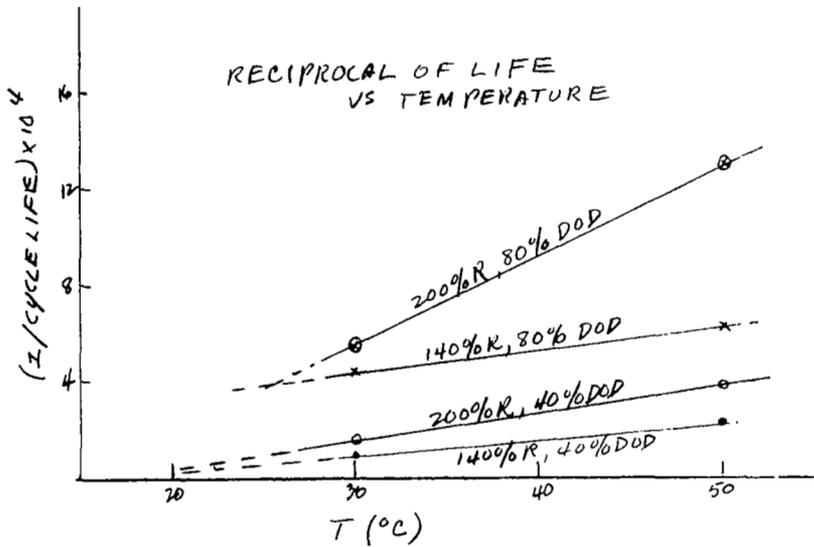


Figure 5-7

THE DISCHARGE - CHARGE RATE COMBINATION

AVERAGE CYCLE LIFE FROM TABLE II

4C, 2C	7500
C, C/2	4100
4C, C/2	4300
C, 2C	4000

CONCLUSION: VARIATIONS ARE NOT EFFECTIVE IN ACCELERATING FAILURE

THE 2C, C COMBINATION BELONGS WITH THE C, C/2; 4C, C/2; C, 2C GROUP (NOT 4C, 2C)

Figure 5-8

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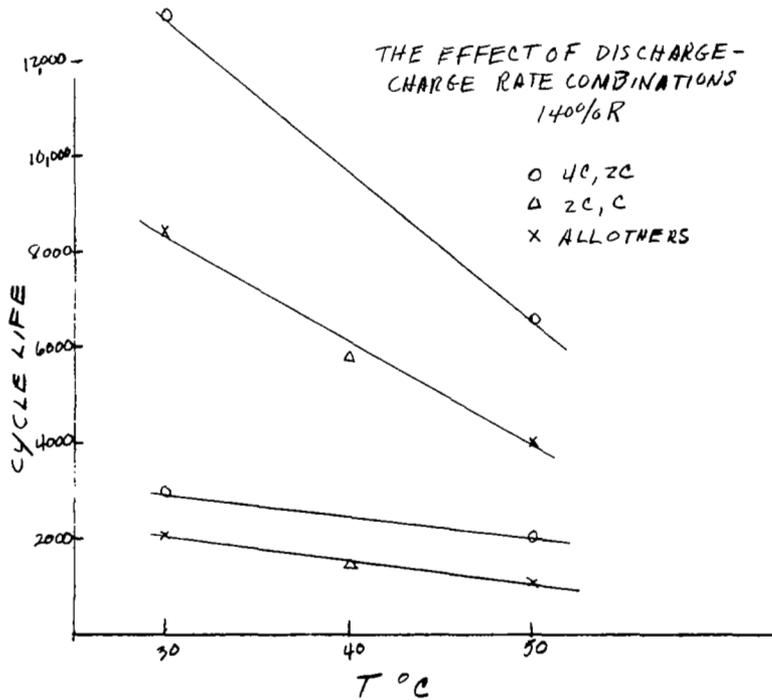


Figure 5-9

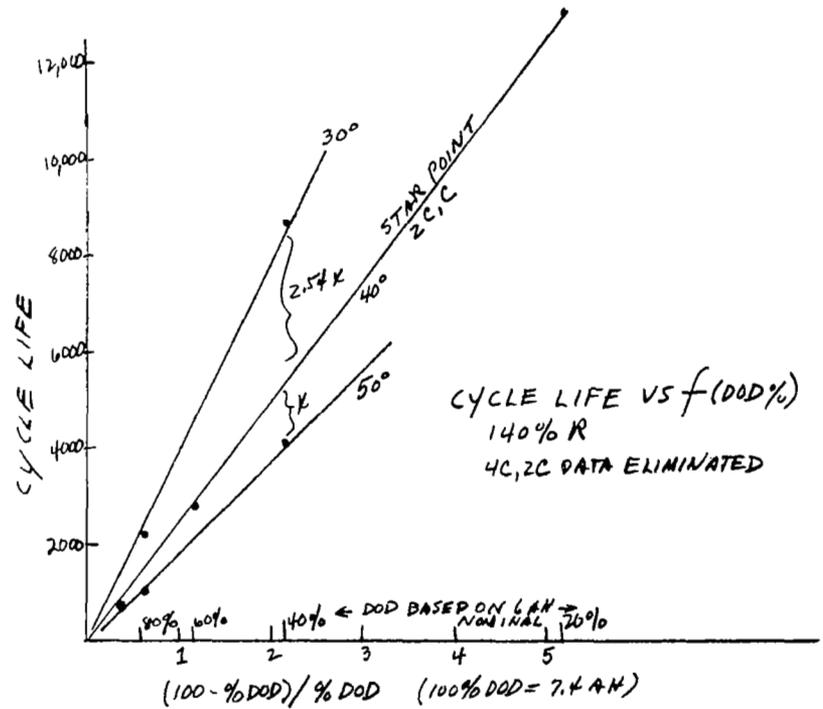


Figure 5-10

THE TEMPERATURE - % DoD COMBINATION  
 CYCLE LIFE VS.  $(100 - \% \text{ DoD}) / \% \text{ DoD}$   
 T = PARAMETER  
 LINEAR IN  $f(\% \text{ DoD})$ , CONVERGANCE AT ORIGIN  
 WHEN  $f(\% \text{ DoD})$  IS BASED ON ACTUAL CAPACITY  
 (NOT NOMINAL)

Figure 5-11

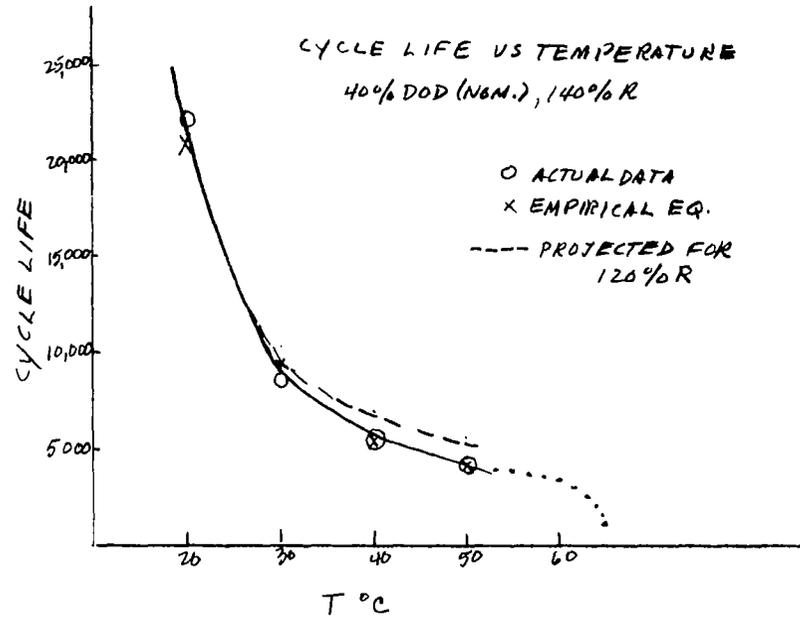


Figure 5-12

THE TEMPERATURE EFFECT  
 A POSSIBLE RELATIONSHIP

$\Delta T$	$\Delta$ CYCLE LIFE
50 - 40°C	X
40 - 30	3X
30 - 20	9X
20 - 10	27X

Figure 5-13

T°C	- (T-50)/10	CYCLE LIFE
50	0	A
40	1	A + X
30	2	A + 4X
20	3	A + 13X
10	4	A + 40X

$$C.L. = \left[ \frac{1}{2} (3^{-(T-50)/10} - 1) X + A \right] \left( \frac{100 - \% \text{ DoD}}{\% \text{ DoD}} \right)$$

X = 600      A = 1900

Figure 5-14

PACK #	PREDICTED LIFE		CYCLE LIFE
	T°C	% DoD	
83N	0	40	156,000
84N	20	20	50,000
85N	0	20	373,000

$\tau = \frac{L}{\sqrt{DOD}}$   
 CONDITIONS FOR 10 YEAR LEO LIFE

T°C	% DoD (nom.)
0	70
10	39
15	26
20	18

Figure 5-15

ACCELERATED TEST DESIGN

- DISCHARGE-CHARGE RATE COMBINATIONS DO NOT ACCELERATE FAILURE
- % RECHARGE ACCELERATES FAILURE BUT NON-LINEARLY. EFFECT VANISHES AT 20°C AND LOWER. TOO LITTLE INFORMATION
- % DOD, T REMAIN FOR TEST DESIGN
- 2C, C RATE COMBINATION CAN BE USED (2C DISCHARGE, c.p. CHARGE)

Figure 5-16

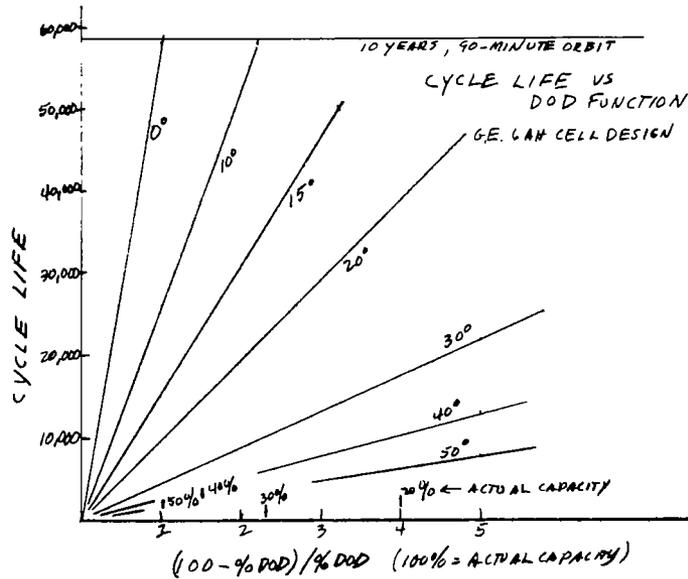


Figure 5-17

ACCELERATED TEST DESIGN  
(90 - MINUTE ORBIT)

FOR DEMONSTRATION OF 10-YEAR LIFE -- 10 X ACCELERATION

- C.P. RECHARGE MODE
- 5 CELL PACKS, MIN.
- T's: 20, 30, 40°C
- % DoD's: 50, 40, 30 (ACTUAL CAPACITY)
- 120% R
- 45-MINUTE CYCLE (2C, C)

Figure 5-18

THEORETICAL EQUATION - 1973

$$\text{CYCLE LIFE} = \frac{1000}{M \times N} \left( \frac{100 - \% \text{ DOD}}{\% \text{ DOD}} \right)^{IT}$$

M IS DESCRIPTIVE OF DEGRADATION RATE

N IS A NUMBER DESCRIPTIVE OF TEFFECT;

IT = 2 IF DEGRADATION RATE DOUBLES PER 10°C INCREASE IN T

Figure 5-19

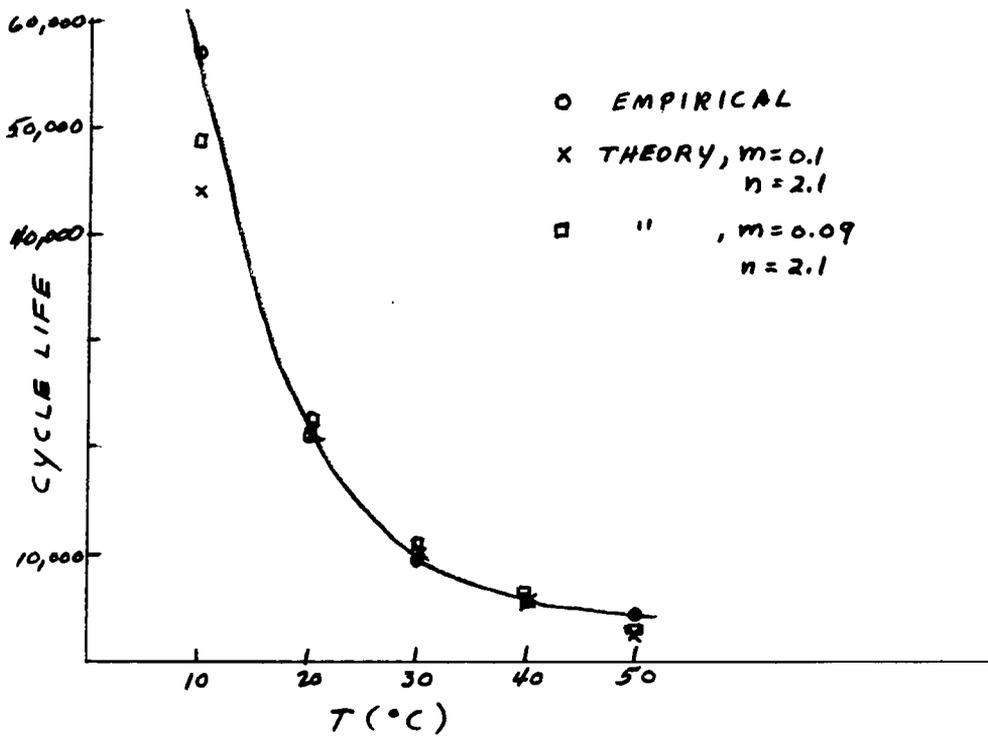


Figure 5-20

## ACCELERATED TEST DESIGN

P. McDermott  
Coppin State College

I have been working on the same accelerated test program that Dr. Landers has. We have come up with some variations on the predicted equations, and I agree on a number of things with Dr. Landers, and disagree on several things. And those I would like to highlight in this talk. It refers to the type of variation of functional changes that occur with the various parameters.

I agree wholeheartedly with Dr. Landers that we have learned a lot about accelerated testing in this program. Because of the lengthy nature of the test and the analysis itself, a lot of things haven't come out yet about how to test out a new accelerated test. But, I think we should move towards this.

Simply, the motivation for accelerated testing is very high. The expectations may also be too high, or overambitious, but that shouldn't deter us from really trying to do accelerated testing. You can't do good development work on batteries if you have to wait four or five years before you can make a change to see if it is going to be an improvement. And the same for very long-term, real-life tests or programs.

Is it going to help if the battery is going to last seven or eight years? So, the Crane accelerated test program possibly was overly ambitious from the beginning in terms of expectations, that we thought we could learn a lot very quickly. But, still I think we have come out of it with an idea of how to do accelerated testing so that we could do it within, say, a year. And that these expectations are more real and more useful.

When I sat down to figure out for myself what lessons I had learned from the program, they came out somewhat like this.

(Figure 5-21)

(These are some things which I had reflected on and which I had learned from the program.)

General observations about accelerated testing.

Lesson 1. Do not make the accelerated test too complicated. Some practical problems that we ran into with this particular test – and, of course, this was an initial large accelerated test program, so what we are really going to say about it is Monday morning quarterbacking, or hindsight. We really had to go through the process in order to learn these things. But I think it is good to reflect on what we have learned.

Too big a test increases the risk of error. As you automate a program you have unknown unknowns that creep in. The automation itself tends to postpone some decisionmaking if something

goes wrong and you are not able to analyze the result on a real-time basis. As you increase the number of packs, you are increasing exponentially the problems of keeping all of that data in good order and being able to react to changes that are going on during the test period.

So, just the size of the program is going to present a problem.

Too many factors complicate the analysis. As I think Dr. Landers pointed out, say that three design parameters may have overly complicated our analysis of the accelerated parameters, the first five parameters. And if they had been left out, the analysis itself would have been simpler.

Lesson 2. Do not make the accelerated test too short.

Dr. Landers mentioned this, and I agree with it, that overstressing the cells may generate a mode of failure that is not "natural." For example, the hydrogen failures were not natural in the sense that you had had a very great degradation of cell components, electrodes and so on. And that is what I think we want to look at, the degradation of the electrodes and the materials within the cell, rather than a sort of short-high-rate zap of the cell that makes it fail according to some rather arbitrary principles; arbitrary meaning is failure at 250 psi or 200 psi when we are trying to figure out a pressure failure.

Lesson 3. Stay ahead of the data. This we found was a real difficulty with large volumes of data that is being taken in a sort of automatic fashion, put on magnetic data tape, and stored for long periods of time.

We found, for example in our post-test analysis that we didn't need every cycle, and voltages every 30 seconds or so on every cycle. So we went through a routine of trying to figure out what is it that we really wanted from the data, and came up editing these 200-odd tapes, magnetic data tapes which contained a lot of data. I figured out once, if all the data was on cards, it would have stretched from Washington to Crane if you put the boxes of cards end to end.

This becomes almost unmanageable at a point.

So, from the beginning, how do you try to determine what data you are going to take? That is what I mean by preplanning the end use of it.

We came down, for example, in selecting the data from these 200 tapes and condensing it down to four tapes (three or four tapes), and what those four tapes contained are the whole life-time of one pack every 30 or 40 cycles. In other words, at cycle 1, 30, 60, 90 and so on, we would pull out fairly complete voltage data on those cycles.

We also compressed the number of samplings at the beginning of life and compressed the number of samplings at the end of life, because we felt during these long periods of the test, the data were not going to be that useful in the sense that the cells were in a sort of equilibrium state and there were not great changes going on there.

Obviously, in terms of recording, you cannot predict the failure at the end of life, you really cannot predict that from the very beginning. But you can predict how you should take the data at the beginning of life when the cells are reaching an equilibrium. And that your sampling procedure itself can cut down the headaches of amassing great quantities of data and not knowing what to do with it afterwards. Edit and clean up the data as you go.

We ran into problems when we adopted the philosophy that we are going to take a lot of data and later we are going to go back and sift through and throw out the stuff we don't want and so on. This is a problem.

If you are not watching carefully when you begin to take data and something is going on within the test itself that may not be recording properly on the mag tape, we have large sections of blank data simply because the retrieval procedure itself was faulty at that point. So you have to stay on top of the actual collection of data.

Lesson 4. Schedule activities properly. I have divided pretest, test, and post-test. We had some problems with concentrating a lot of our efforts at the wrong time. The pretest should be basically working out all your hardware problems, and early testing the system so that you don't have failures in the middle of the test with, say, data acquisition.

Most of your effort should go into making sure that once the test goes on line, the management of the data from that point on is going to be fairly straightforward.

In the test phase, concentrate on the data acquisition and not on the analysis of the data. We tended to take fairly spotty data, the test cells had not been on test very long, and working equations and grand regressions over a very small data base.

Now, part of this is needed to tool up your analysis so that by the time all the data does come in, you will have the tools ready, which is the post-test. Concentrate on the data analysis after the cells have failed, or most of the cells have failed.

This will tend – you don't run out of steam too fast. I think we had a tendency because a lot of the analysis effort went on too early, that we were sort of over that hump before we really had enough data to do the proper analysis.

Lesson 5. Do not overestimate complexity of batteries and frustrate your efforts. This is not in jest. When you take a large test program – and particularly using large statistical analysis techniques that are developed in other accelerated testing of other types of components – you may have some problems. For example, testing transistors; accelerated testing other components may fit a particular model easily because you can generate reliable distributions and so on, which pretty much map the failure mechanisms that are going on within the component.

But batteries tend to have more “inherent” variables either through manufacturer's design variability, that predictability of the battery itself is not that clean. Therefore, we really need to look for the first order effects and not concentrate too much on finetuning it.

I remember a quote in Dave Pickett's Laboratory back at Wright Patterson of Edison which said when it comes to accumulators, man's inherent capacity for lying comes out. In other words, the nature of the beast itself is tough to deal with, so don't oversensitize your analysis and possibly miss your main effects.

Lesson 6. Choose your stress factors carefully.

(Figure 5-22)

I would like to discuss the better parameters used for accelerating testing and why. Pretty much the same conclusions would be reached as those of Dr. Landers'. I have done it in a slightly different way.

These are the test parameters as seen in the star point, center point test cells. I have tried to see what the effect would look like if you select out each parameter, holding everything else constant. I have presented this in the past in other workshops, so I have done mostly a summary here.

Depth-of-discharge temperature and so on down to volume of KOH as shown.

Then I have shown a range in the star point test.

If you are looking at DOD, this would mean 20, 60 and 100 percent would be the three variables, and everything else would be the same. So for the star point we would be looking at three packs, 20, 60 and 100 everything else the same. I found the variation over that range is around 13,000 cycles. The cycle life exponentially increases toward lower stress.

I guess the way I look at it is the DOD is not a function of 100 minus DOD over DOD as Dr. Landers has found. What I have used in my model is that it is exponentially changing and that the function is E to the DOD, the power of DOD. I found that its usefulness as an accelerator and a predictor is very good because when the cycle life is plotted or logged against DOD, it comes out fairly linear.

What might be happening here is that Dr. Landers' function and this function are probably mapping each other's fairly closely. That is 100 minus X over X is in that range to E to the X. I don't know how you expand E to the X. You might find a series which comes closer to Dr. Landers' function as a close approximation.

So probably in the range that we are dealing with, our functions are fairly consistent with each other. But I think when we get to lower DOD, that's where we get quite a bit of difference.

When I start extrapolating down to very low depths of discharge, I am not getting 100- or 300,000 cycles, I am getting much less. So I think we might be mapping our functions in this region, but when we go below that region our functions are really diverging.

Temperature I put is a good accelerator and a predictor. Not very good, but good.

The variation in the range that we considered here is about 5000. It is approximately linear. It is not actually linear, but within that range it is close enough to consider it linear.

So when I do my regression equation, I put it in as a linear function. Below 20 degrees it does become possibly very nonlinear, but it is close enough to use it at least in a regression equation.

The recharge rate is approximately linear, at least in the range that we are dealing with. Here I am disagreeing with Dr. Landers also.

The effect of the variation is not as great as the other two, and I would say it is a fair predictor.

When I put up the regression equation and I build in a linear recharge rate, I will show you that it comes out as fair, but not as good as the other two.

Charge and discharge rate, I agree with Dr. Landers, is problematic. They can accelerate, depending on various combinations of charge and discharge rate. They can accelerate deterioration, but they are not very good to use as predicting because you are not really sure what effects are going on there.

Dr. Landers showed, for example, that 4C, 2C actually prolongs life, which is sort of against your intuitive feel, perhaps. So it is not very good as a predicting tool.

Precharge – and here it is parabolic in nature with the high point at mid-range. It may not actually follow a parabola, but it is sort of a haystack type thing. That is, the low-charge rate and the high-charge rate show the lower-cycle life and midrange shows the higher-cycle range.

This becomes a problem in using it in the regression model because as you go towards what you conceive of as lower stress, that is lower charge rate, lower discharge rate, cycle life is actually going down. Whereas when you are going to lower temperature, cycle life is going up.

So you are interacting two variables. One is going up while the other is going down, and it is hard to control that. They are sort of nulling each other out.

Precharge and KOH and volume KOH, these are the cell design parameters. And their effect is not large.

These two were parabolic in nature which meant that the range that we were taking had this as one extreme and that as the other, and midpoint was the highest cycle life.

Here again it is problematic to use it as a prediction model, or in the prediction model. If you are going to use parameters for prediction, they ought to all be increasing in the same direction as your lowering stress.

That may not be true if you are trying to use accelerated testing for a new cell design. Suppose you want to test out and see if the percentage of electrolyte for a particular test should be low, high, or in the middle. In that case you would definitely want to box the range. In other words, you would want to try to get the most stress at each end, but not to be used in prediction, but to be used mainly for teardown analysis after it is over to look at what the effects of the accelerating were.

The volume of KOH turned out to be the lowest variation. It was approximately linear in effect, but its effect was too negligible. In other words, that range just was not large enough to make a difference.

(Figure 5-23)

Now here are the predictions that I have based on my nonlinear regression equation and this took the Crane data, so it includes pretty much all of and maybe more of the data than Dr. Landers had in his equation. I'm not sure. This took almost all the packs.

This is the equation itself. Cycles to failure. Here is a linear recharge term, and here is a linear temperature term, and here is the exponential DOD term. And just to see what the effects would be of charge rate and discharge rate, I threw those in as linear combinations at the end of the equation to see how the computer would handle it.

Now, I say these are linear terms, but they are multiplied times each other, which makes them really interacting terms. And if you interact recharge – looking at this as a quadratic, if you recharge multiplied by temperature comes out as one of the terms with  $b_2$  as a coefficient, we are not holding them only to linearity. They can be having some interactive parabolic effects in here, or hyperbolic effects.

Here are the predictions that come out, limiting this equation only to  $b_1$ ,  $b_3$ , and  $b_4$ , which is a constant term out here, no recharge term, keeping temperatures in the equation and a depth of discharge. So this case really shows only DOD and temperature.

This case shows it with recharge. This shows it also with charge rate and discharge rate.

Now the coefficients themselves change quite radically. Some of them do, but these don't. The predictions of the normal packs don't change that much.

Now this 86 is the pack that Dr. Landers predicted what, 22,000?

LANDERS: No, I didn't predict it. There were already three cell failures on it.

McDERMOTT: Three cell failures starting around 18,000 which is where cell failures start.

LANDERS: Two of them still going beyond 24.

McDERMOTT: And these, in my IE CEC paper from which this slide comes out of, I tried to see where this – well it's obviously too low a prediction. What may come out of this equation is a very conservative prediction, about the lower limit at which you would anticipate cell failure.

My predictions don't get anywhere near what Dr. Landers' does in terms of  $0^{\circ}$  C. Forty-six to fifty thousand is probably the highest my prediction is going to run. And I guess this is probably 10 years. Would that be a 10-year prediction, something like that?

All right.

Now what I have done is I have taken the regression equation and now where do we go from here in terms of designing a new accelerated test?

I took that regression equation with only DOD and temperature. We have to give up some of our accelerating parameters simply to limit the number of packs that we would have on test.

I agree with Dr. Landers, we should limit it to temperature and DOD which have most of the predictability base for a reasonable estimate.

I rearranged the equations so that temperature would be on one side and everything else on the other. Here is DOD. I put charge rate and discharge rate in here simply to estimate the time of the cycle. I am not using those as accelerated in terms of the data, but simply to put into the equation how much each cycle is going to take.

I have plotted temperature versus DOD. If you anticipate the test to only last one month, three months, six months, nine months or a year.

So what I am doing is parametrically looking at, suppose I want a 6-month accelerated test, what should I put the half dozen packs at in terms of temperature and DOD?

What you can do essentially is pick a temperature, 10 degrees here. This is based on the Crane data. That is, the coefficients I would use in this equation are from the Crane data. What this says is, if I took that generation of cells, 1970 GE with nylon separators and so on, and if I ran them at 10 degrees and 80 DOD, they should fail in six months. If I took  $20^{\circ}$  C at 70 DOD, they would fail in 6 months, and so on.

So the idea is, try to set up a test matrix where most of the cells are going to fail around the same time, or within a couple of months of each other, so that you do not overstress them so that they fail too quickly. And don't understress them so that they are lasting two years.

You are trying to pick a time within which you would need to get results. Say if you were doing some program management and you wanted to select six months as the time for your accelerated tests, then you could make some judicious choices in terms of setting up the matrix.

Here is a table for several different combinations of charge rate and discharge rate. Here is the DOD, and these would be the temperature. This is based on a six-month test.

Suppose we want a six-month test, 70 DOD, and 23° C would be where you would set the parameters for that particular pack; 60 and 32, 50 and 39. So you might set up, for example, five packs that would vary temperature; interact essentially temperature and DOD. Then you would use these cycles to failure; the data for cycles to failure and plug it back in the reduced regression equation. By reduced is meant the only variables that you are interacting are temperature and DOD. Therefore, the equation would turn out to be a constant minus temperature times the exponential function of DOD.

You would essentially fit three coefficients, and then using those coefficients you would predict how the cells that you have on test would last in less extreme conditions, say 20° C or 0° C and 20 to 40 DOD.

I suspect that when using this process you are going to end up with predictions that are much lower than Dr. Landers', because what I have done is try to map that range below 20 degrees with an equation which is going to ultimately deliver what we would estimate is a reasonable failure in normal life.

## DISCUSSION

LEAR: Pat, your equations up there, or your summation said your recharge rate — you got a fair indication from recharge rates from 110 to 200.

What about below 100?

McDERMOTT: Well, we don't actually know that except to say that my predictions in case 2 were based on a linear function. And my predictions are coming out low.

So I would suspect between 110 and 100 percent recharge, that it is increasing there, possibly dramatically, that I don't see, in other words, to explain the difference between what we are actually seeing with the normal packs. So it might be that that recharge rate, or the interaction of that recharge rate below 110 is fairly important.

I would probably set up an accelerated test. I would take recharge out of it, and I would not use a constant current charge. Also, as Dr. Landers has suggested, I would just have a voltage cutoff or something like that. I would take charge rate and recharge out of it as far as accelerated parameters, and just lean heavily on temperature and DOD.

LEAR: Now, I have a second question for temperature. You were referring to temperature. What is that temperature? Is it an absolute temperature, is it an ambient of the test specimen? What?

McDERMOTT: The samples are in a temperature box that are set at so many degrees C. So it is, yes, based on degrees Centigrade. It is the temperature of the environmental box that they are in.

There was some range in terms of the thermistors that were on the battery itself. I think they ranged up to five degrees outside of that, and that's one of the problems with trying to look at this too precisely and saying this is it at 10 degrees and this is it at 20 degrees. It might be you are looking at 12 1/2 to 13 degrees and 23 degrees or so in the actual environment.

That is why I keep it in what I call first-order effects; not trying to compress too tightly what you consider is the sensitivity of even the prediction equations to those variables themselves. For example, DOD; if you take it as an absolute, then 100-percent DOD is only taking out six ampere hours in the cell, which has a capacity of seven or eight.

But in the regression equation, factors like that really come out in terms of the coefficient so that the coefficient takes care of differences in capacity. I am just saying you don't want to think that your test is actually being performed at 10° C exactly. It is not.

RITTERMAN: Your parameters are based on the treatment of the cells with the exception of the one with the electrolyte.

Nickel-cadmium cells have been changing in the last few years. Teflonated coating on the negative electrode, we have lighter load, we have different toxic center, and we have different toxic risk. We are going toward electrochemical impregnation on the positive electrodes.

Would you say that your model is valid for these newer types of cells, especially since the basis of your model is 67 to what, 78 or something like that?

McDERMOTT: What I would say is the form of the equation is a problem, but the coefficients would have to be determined by actually putting yourselves on test.

RITTERMAN: *So you cannot make any prediction on a new type of cell based on . . . .*

McDERMOTT: I would take the coefficients we got at Crane and use those as the first approximation to determine whether you want your test to last six or eight months. Your test may actually end up lasting a year if your cells are twice as good.

But it is trying to get a first approximation for how you should set up your matrix, and then you run your test matrix. You get your results, you recalculate the coefficients and then you . . . .

RITTERMAN: You have to test the new cells.

McDERMOTT: You have to test the new cells. I don't see any way of taking these results and making a prediction on your cell. I just don't think it is going to work. A lot of this was outlined in the IE CEC paper, if you want to look at the actual methodology I would use to set up the test. I just didn't have time today to actually go into that.

# GENERAL OBSERVATIONS ABOUT ACCELERATED TESTING

- LESSON 1 DO NOT MAKE YOUR ACCELERATED TEST TOO COMPLICATED
- TOO BIG A TEST INCREASES RISK OF ERROR
  - TOO MANY FACTORS COMPLICATE THE ANALYSIS
- LESSON 2 DO NOT MAKE YOUR ACCELERATED TEST "TOO SHORT"
- OVER STRESSING THE CELLS DISTORTS RESULTS
  - FAILURE MODE NOT NATURAL
- LESSON 3 STAY AHEAD OF THE DATA
- PREPLAN THE END USE OF THE DATA AND DO NOT RECORD EVERYTHING
  - EDIT AND "CLEAN UP" DATA AS YOU GO
- LESSON 4 SCHEDULE ACTIVITIES PROPERLY
- PRETEST - RESOLVE HARDWARE PROBLEMS AND DISAGREEMENTS ABOUT TEST OBJECTIVES HERE
  - TEST - CONCENTRATE ON DATA ACQUISITION
  - POST-TEST - CONCENTRATE ON DATA ANALYSIS
- LESSON 5 DO NOT OVERESTIMATE COMPLEXITY OF THE BATTERIES TO FRUSTRATE YOUR EFFORTS
- BUILD IN TEST FLEXIBILITY
  - LOOK FOR FIRST ORDER EFFECTS
- LESSON 6 CHOOSE YOUR STRESS FACTORS CAREFULLY
- LIMIT SIZE OF TEST MATRIX

Figure 5-21





## DEVELOPMENT OF FAILURE MODEL FOR NICKEL CADMIUM CELLS

A. Gupta  
Jet Propulsion Laboratory

At JPL we have been developing a method of life prediction of NiCad cells during the last four months.

(Figure 5-24)

This is the approach: We are trying to develop an understanding of the mechanisms of degradation and failure, and at the same time develop nondestructive evaluation techniques for NiCad cells.

The mechanisms of degradation and failure involve development of a statistical failure model and also development of chemical or quasi-chemical models of degradation starting with the very basic assumptions of chemical processes leading to failure.

At the same time, we are trying to develop nondestructive evaluation techniques, or NDF techniques as they are called in the trade. Once these are developed, and we do exploratory work, validate them; then they require calibration through real time and accelerated testing so that they can be used to predict usable life.

(Figure 5-25)

This figure shows the approach to failure modeling in greater detail. Test data from Crane and elsewhere in the literature have been used to develop statistical failure models using extreme value statistics. Extreme value statistics is a statistical approach that has been found to be very useful in modeling failure data in widely different systems; for example, transistors, as Dr. McDermott pointed out, and other systems, such as rotors in jet engines.

Extreme value statistics assume that failure occurs in systems due to presence of flaws or defects greater than a critical size. It starts out by assuming or postulating a certain flaw size distribution in the specimen, and this size distribution remains constant as the specimen is aged or cycled. The size of the individual flaws increases as the specimen undergoes aging and as the size of the biggest flaw exceeds the critical area or size failure occurs in the specimen. This statistical approach is therefore different from regression analysis, no matter what our model is. Regression analysis assumes that there is a normal or Gaussian distribution of failure data points across or about the fitting line drawn from whatever model you have. On the other hand extreme value statistics assume that failure distribution is skewed and the underlying flaw size distribution that causes failure is also skewed.

Simultaneously we are working on a cumulative damage model. This starts out with a fairly basic assumption that the flaws, which are supposedly causing failure according to the extreme

value statistics, interact with the electrons to cause damage or increase in flaw size. As this damage accumulates in the battery, it ultimately undergoes failure when the size of the flaw exceeds the critical value postulated above. Electrons here may mean electrons or holes, that is, positively charged ions.

Here I want to emphasize that at this stage of our work – we have been working only a few months in this project – we are not attempting to define flaws. We haven't attempted chemical or physical characterization of these flaws. In fact, there could be many parallel reactions leading to degradation. All we have stated is that there are reactive sites or flaws in the specimen that interact with ions or holes causing damage. Therefore the flaws have two characteristics: (1) they are capable of undergoing a redox process, and (2) they cause failure.

(Figure 5-26)

This slide shows the quasi-chemical model in somewhat more detail. There is an error in this slide. This should be  $s$ ;  $n$  is the number of charge-discharge cycles,  $m$  is the order of reaction, and  $f$  is the faradays of electricity passing through the battery. Integrating the rate equation one gets the model.

Now, making an assumption that  $m$  is equal to zero, we get the final equation which is our chemical model. This model is based on the one assumption that flaws interact with electrons causing damage and eventually failure. There are two main parameters in the equation;  $\Delta E$  which is activation energy which defines the temperature dependence, and  $m$ , another parameter that describes the rate dependence on DOD.  $C_0$  is the capacity of the battery, and  $g$  is a function of charge-discharge rates. We don't yet understand how charge-discharge rate affects life. Now, by keeping everything else constant we can plot the number of cycles or the log of the number of cycles to failure versus the absolute temperature.

(Figure 5-27)

We obtained a fairly good approximation of a straight line, the slope of which is the activation energy. It is about 5.7 kilocalories per mole. This value agrees reasonably well with literature data. This plot was obtained, by the way, by fitting data from the Crane tests. These data are in good agreement with literature which go from about 5 to 7 kilocalories/mole. This value is actually quite low for a chemical process. It is typical of a physical or a transport process. So we get an indication here that probably the rate limiting process leading to failure is a transport process. I don't want to make too much of this, but low activation energy is a clue.

(Figure 5-28)

Once the activation energy was determined, all of the Crane test data (now when I say Crane test data, I mean data based on individual cells, not cell packs), were then normalized to one temperature, 30°C in this case, and then we plotted log of cycles-to-failure versus log of depth-of-discharge. The slope of this line gives the value of  $m$ . In this plot, we have fitted both Crane data and literature data in the same line and the fit indicates two things: (1) that the simple model

seems to fit the failure data adequately; (2) the fact that both Crane data and literature data fit not only the same slope but the same intersect in this equation means that there is some internal consistency between the Crane tests and literature data. We also have some points considerably outside the line (this is a log scale) at high depths of discharge. We don't know why these points do not fit this line.

From the slope we determine  $m$  which comes out to be 1.5; and the activation energy, as I said before, came to 5.7 kilocalories.

Using these two parameters, all Crane data were then normalized to a given temperature and depth of discharge. We chose 100 percent depth of discharge and 30°C. But any value of DOD and temperature may be chosen.

The next slide then shows application of the Weibull distribution to the normalized failure data.

(Figure 5-29)

Weibull distribution is a given (postulated) initial distribution of flaw sizes in the specimen. The distribution is given in the equation. Beta is known as the Weibull parameter. When the flaw size exceeds  $c_f$ , failure occurs.  $\phi_f$  is the cumulative frequency of flaw sizes. Now we can substitute  $n_f$ , red for  $c_f - c_0$  from the chemical mode.  $n_f$ , red is the normalized life frequency.

(Figure 5-30)

The next slide shows a typical Weibull fit. The fit is really quite good. Here we have plotted the log of  $n_f$  which is cycles to failure to a population variable which is actually a function of probability of failure. The slope of this line is beta, the Weibull parameter, which defines the initial distribution of flaw sizes, which must be constant if the Weibull model is applicable.

The test whether this failure model applies to this system is whether beta remains constant, in other words, if the fit is linear. And here we find that for very large variations of depths of discharge, temperature and other variables, beta is constant. These data have been segregated according to charge-discharge rates since we don't yet know how charge-discharge rate affects life. We can say however that the effect is small.

From this intercept we can calculate the most probable reduced lifetime, extrapolated to 30°C and 100 percent depth of discharge. Using this model we can calculate the most probable reduced lifetime for any condition such as 20°C and 20 percent depth of discharge, by simple substitution to that algebraic equation that I showed.

(Figure 5-31)

The next slide shows another Weibull fit for the 4C:C/2 charge-discharge rate. Again the fit is pretty good, and the reduced lifetime is obtained from this intercept here.

There are some scattered data that show pretty significant deviation, and these are the same data points that also showed deviation in the equation where log of depth-of-discharge was plotted versus log of cycles-to-failure.

(Figure 5-32)

The next slide shows another set of data fits for this charge-discharge rate  $C:C/2$ . This is the beta value that can be obtained from the slope, and it turns out that the beta value is fairly independent of CR or DR. It varies from about 2.5 to 3.5 no matter what the charge-discharge rate is. This is one of the most promising aspects of this attempt to apply failure models to this system; the fact that the value of beta remains constant over even widely different charge-discharge rates as well as temperature from 20 to 50 degrees, depth of discharge from 20 percent to almost 100 percent.

(Figure 5-33)

The next slide shows another such fit. In fact, we have fitted most of the Crane data, 360 data points to four of these Weibull plots. There are 75 points in each of these fits.

One of the things that I wanted to mention before I go into our description of our work on development of NDE techniques is something which relates to a question that was asked Dr. Landers. The question was, does the lifetime or cycle life depend on the cycle period, or does it just depend on number of cycles?

The answer from our model as well as the test data is that life is limited by the number of cycles rather than dependent on the time during which those cycling tests are carried out. This indicates very strongly that the rate limiting process causing failure is a transport process. Because, if life was limited by any other factor such as a chemical process, then there would be a strong dependence on the actual time spent in testing.

And this again, therefore, reinforces our view that the rate limiting process is probably a diffusion controlled process or a transport controlled process, which we can speculate could perhaps involved diffusion across the double layer or whatever. These types of speculations, therefore, indicate what kind of mechanistic investigation, such as surface characterization, spectroscopy, etc., that would be appropriate to do on these electrode surfaces, and the double layer.

(Figure 5-34)

The next slide shows another bit of information that we obtained from our model. It turns out that reduced most probable lifetime – remember now that the reduced lifetime is the normalized most probable life expectancy of the cell – depends on the cell capacity and number of plates.

So, using this equation and knowing the value of beta, we can predict how life will decrease or increase or change as the cell capacity changes.

This model predicts that the life, most probably reduced lifetime, life-cycle expectancy should decrease as the number of plates increase, or the capacity increases in the cell. This, of course, is a testable prediction.

(Figure 5-35)

The next slide shows what we have been trying to do in developing nondestructive evaluation techniques. We have been measuring complex impedance on sealed NiCad cells. Complex impedance has been applied before to NiCad cells, so I don't really want to go into it in great detail.

This is a plot of the imaginary part of the impedance, or the reactance versus the resistance, the real part of the impedance.  $R_s$  is the solution resistance. The height of this point gives the double layer capacitance, and the diameter of the half circle here gives the resistance of the charge transfer resistance, and the slope is the Warburg impedance which is related to the diffusion across the double layer. When we applied this technique, this is the shape of the curve we would expect if this simple equivalent circuit is a good assumption.

(Figure 5-36)

The next slide shows the results when a fully discharged NiCad cell was used to measure complex impedance. When the cell is fully discharged, only the cadmium electrode had any capacity left, and therefore we are really measuring the cadmium electrode alone because the nickel electrode acts like a very large capacitance and is shorted out at high frequencies. The results show a fairly good approximation to this very simple model that was used to model the cell behavior, and from this slope of the linear portion we can calculate the diffusional impedance. The objective now is to measure these parameters such as the reactance and the resistance as a function of cell cycling. That is to say, we would like to cycle the cells to various numbers of cycles under given temperature and DOD and see if we can detect any changes in impedance parameters.

This would be a completely empirical approach trying to find out if we can correlate any of these parameters, for example, the charge transfer resistance, or the double layer capacitance to the cell life. And if there is a correlation, then we may be able to predict the life of that particular cell or cell pack.

I think this is an important objective because even if we have very accurate life prediction models, they still will give us a certain probability of life for a population of NiCad cells and what we really need to know is the life of a particular pack that goes up in a certain spacecraft. Therefore, if we can come up with an NDE technique – and I might be unduly optimistic about that possibility – we would be able to then actually predict life of a particular cell pack. If this is possible, we can probably fit the measurement into an assembly line as a quality control procedure.

(Figure 5-37)

The next slide shows plots of diffusion of impedance and they are calculated, actually. But the value of diffusion impedance in this cell, Warburg impedance is a function of when it is fully discharged.

(Figure 5-38)

The next slide shows the data obtained when complex impedance measurement is carried out on a partially charged cell. The data now is a lot more scattered and is much more difficult to interpret. This is more or less where we are. One of the several other possible diagnostic approaches we might take is to put in a third electrode in the system so we can treat each of these plates separately.

## DISCUSSION

LANDERS: I think that these three papers showed a process of growth and sophistication of data treatment. We older types look at pictures, and I will have a little bit more to say about that.

First of all, I have these comments: The design variables which were considered on this turned out very happily, from the manufacturer's point of view, because they showed that a lot of his manufacturing processes in terms of the three variables that were looked at, do not have to be held too closely in the manufacturing process.

Second, the percent DOD function which I used comes from very simple theory. Actually, it is arithmetical in nature. What it comes from is that supposing you are running an 80-percent DOD. That means you can only have 20-percent degradation before failure.

On the other hand, if you are using a 20-percent DOD, you are going to have 80-percent degradation before failure.

It is that particular fact that results in the DOD function which I used. Intuitively it has got to be so simple that it ought to be a close approach.

The temperature function is very important, obviously, in predicting those low temperatures. First of all, in the empirical equation which I used there, I was trying to fit a 50° C data point.

Obviously using trebling as a temperature effect is going to lead to very high temperature cycle-life values at the low temperatures, and I don't believe that myself.

The theoretical equations which I finished with in my talk used doubling, and this does not quite fit the 20° C point.

As you may recall, my doubling equation showed it to come out about 10,000 cycles lower. What this means is if the so-called theoretical equation is a better fit than whatever the actual situation may be at low temperatures, the theoretical equation is going to predict much lower values of cycle life at lower temperatures.

Finally, I can't agree with Pat about the temperature functions of linear, and I think your data indicates that also.

GUPTA: Temperature functions almost always have to be exponential, because whether we have a physical process or a chemical process, usually there is an activation parameter. It is difficult to come up with a molecular level understanding of a process that varies in any way with temperature other than in an exponential manner. This is because this exponential temperature parameter is related to the Boltzmann distribution.

May I just summarize a little on the DOD. The model that we used for treating DOD is that the DOD tells us how many electrons are passing through a cell, and therefore how much charge is being transported, and therefore that determines the number of moles reacted. And here we expect a polynomial dependence. Now whether it is to the power of 1 or to the power of minus 1 – for example, Dr. Landers says it is to the power of minus 1 – or it is to the power 1.5, we don't know for certain. Our model, used to fit the data from Crane, gives 1.5 to perhaps plus or minus 10 percent accuracy.

This result has implications about the nature of the reaction that is going on. In other words, it tells us the molecularity of the reaction, and it is difficult again to understand the value of less than 1, unless we are talking about a rate limiting process that has nothing to do with the movement of charges in the battery. Therefore, we expect  $n$  to be higher than 1, and we expect them to be less than 2, because if  $n$  was more than 2 it means physically that two or three electrons must converge to a site before carrying out a reaction, which is an unrealistic expectation. So physically it makes sense to have it between 1 and 2.

McDERMOTT: I'm not suggesting that the temperature dependence of chemical reactions is linear. That's not what I'm saying.

I'm saying that the cumulative effect of all the reactions going on in the cell has a certain effect on life. We are not looking at the cell. It is just an electrochemical experiment. We are trying to say what is limiting the life and what's the functional relationship.

When we take Crane data, we find over the limited range we are dealing with, that if you just plot temperature versus – with everything else held constant, you will find it approximately linear.

Sam, didn't you do that?

LANDERS: Yes.

McDERMOTT: You found up to a certain point, 50 degrees, that you do have this. Now you might have some very interesting things happening below 20 and to zero that are not linear, so that extrapolation in that range is very tough.

I would like to ask you, did you make any prediction of the low temperature and lower DOD cycles to failure based on your equation?

GUPTA: Yes, I did. But let me first clear up this temperature debate by saying, I think Dr. McDermott's approach and our approach are complementary.

You are trying to fit the data as you see with temperature, and the linear fit seems to do a good job or adequate job.

What we are trying to do is go beyond this fit, at least in terms of our program. We are trying to use this test data to develop an understanding of failure mechanisms. As soon as we try to do that, we have to have some kind of an idea about an activation energy, because that gives us some kind of information about the chemical changes that are going on which lead to failure.

Therefore, I think that both of these approaches can be used. If you use Dr. McDermott's approach within its limits, it may be just as well. Yes, we have made predictions. This is what I mean by most probable value of reduced lifetime.

(Slide)

From this intercept here, we can calculate, for example, the most probable life of the battery under various conditions. And it turns out that this is about 1420 cycles. That's at 30°C and 100-percent DOD. This is an extrapolated value or normalized value.

So we go to 20-percent DOD, we just apply the algebraic factor, 500 divided by 20 to the power 1.5 to this number. We multiply it by that and then we apply our temperature dependence parameter, which we have deduced from the data, which is  $E$  to the power minus 5.7 divided by two times whatever temperature we have. If you work it out — in fact, I did do one calculation — it turns out to be roughly 7.5 or 8 years of cycle life. It is a fairly trivial calculation to perform, so the information is right here.

GROSS: Please explain the ordinate and axis on that figure.

GUPTA: This is  $n_f$ , the number of cycles to failure reduced to normalized using the chemical equation. If you want to see it, I can go back to the previous slide. This is  $P$  of  $n_f$  reduced. This is a population variable, and this is a function of what I call  $\Phi(n_f)$  which is the cumulative frequency of failure or probability of failure at  $n_f$ . The quantities are derived by using standard statistical techniques. What we do is to list the number of cycles to failure and give them integral labels like 1 to  $l$ ; for 76 cells, there would be 1 to 76.

Then, suppose we have  $n_f$  for the  $i$ th number in this series, so that then  $P$  would be  $i$  over  $l$  plus one.

In other words, if you take the highest number, then  $P$  would be  $L$  divided  $L$  plus one. This is an arbitrary but accepted procedure which is used to estimate probability of failure,  $\Phi(n_f)$ . This is available in any textbook on reliability theory.

HENNIGAN: The initial purpose of the test as we set it up was to see if we could get some profiles in, say, a week or two at the parameters we ran to tell you whether we had good cells or bad cells. But I was a little dubious of that.

At least, we thought maybe we could get something in about a month or two: an accelerated test that we could take a sample from a lot, let's see, yes, we got good cells and bad cells, but it appears that it is coming along pretty good. I think Pat said it looks like given a six-month period we could test cells and determine whether they are good or bad.

Now I understand that there has been some disinterest in this program at the levels that be. And I was just wondering if someone would want to comment on that?

LANDERS: One more comment. I think that Pat has done us a great favor in iterating the lessons we have learned from this test, in view of, well let's say, the philosophy of accelerated testing.

GROSS: My understanding when the test was in progress was that there was a possibility that data could come out of the test to give an indication of when failure would happen prior to actually getting the failures.

In the analyses we have seen today, correlations show essentially how you could set up a test, but you would have to run the test to complete failure.

So the question is, were there any kinds of predictors that were determined during the test to either be valid or invalid to predict when failures might be because of voltage degradation and other things?

GUPTA: I would like to add a comment to that. That is the purpose of our work on trying to develop NDE techniques. I think that using electrical properties of cells such as cell voltage to predict its life is not going to work.

We think that the only way we can really predict life of a particular cell pack and not of a population is to make some kind of nondestructive measurements of properties which are different from the properties we are measuring when we are following degradation of properties. We think we have to make measurements of special properties, using nondestructive evaluation techniques which will eventually correlate with life.

McDERMOTT: We tried to look at that in terms of the analysis of end-of-discharge voltage, end-of-charge voltage, things like that, the slope of the discharge curve at half capacity. And I would say we have not done a thorough analysis of that part of it.

One of the problems was that we had so much data, and that was one of the reasons for getting a reduced, edited version of the data, in order simply to attack the problem. What we have done is try to take 30 representative cycles out of the whole lifetime of the cell. All right. This would be clustered more at the beginning of life and more at the end of life. And then to try

to analyze various parts of the discharge curve, the shape or the knee right as you start to discharge, the slope of the discharge curve as a rate of voltage change and so on.

I would say that is still in the future in terms of using that for predicting what you were talking about. One of the problems is, once the cell goes into sort of an equilibrium type test phase, initially you will go through some changes in these parameters, then it will flatten out, and it will go like that for years on a relatively mild cycling condition. And you don't start seeing warning signs until you are almost at failure, unfortunately.

So, I would say it's a very sensitive, the voltage changes and so on, issue that we are still pursuing. One problem we had is when you look at one voltage curve, you tend to have fluctuations in other parameters that throw you off. For example, if you look back at the temperature data, the box might have changed temperature a few degrees and so on, or the night before the lights went out and they stopped the test and they started back up again, so it is going through one of those equilibrium problems again.

So it is not an easy thing, but what we are trying to do is attack it by looking at 20 to 30 representative cycles. Now when I say that I'm saying we are taking a cluster of cycles, three cycles, and averaging them together. For example, cycle 25, 26 and 27, and then 50, 51, and 52 and so on, and then averaging clusters of those to try to work out some of these ripple effects of just selecting one cycle which could have some other influence in it.

We are still working on it, but we are probably a little further off from that than we are from the other analyses. But I think, ultimately, that is going to be the best test when you can look at the voltage and see some of those changes. That's the best nondestructive means I think we have at our disposal, since you get telemetry from the spacecraft, in order to look at the voltage and run a profile and so on and see if you can predict how long it has got to go.

LACKNER: I'd like to get a bit of clarification on your complex impedance diagram, particularly what was the significance of Zed double prime, or Z?

GUPTA: The Z prime is the real part of the impedance. The Z double prime is the imaginary part of the impedance.

LACKNER: What does that mean in English?

GUPTA: It probably means Z prime is resistance, and Z double prime is the reactance. In other words, if you write the impedance as a complex number,  $A + jB$ , then the coefficient of  $j$  is the Z double prime, and the real part which is  $A$ , is Z prime. It is measured as a function of frequency, and this is one area where we have done things slightly different from that that has been reported in literature.

We have looked at a very wide range of frequencies. So we just measured this impedance as a function of frequency.

LACKNER: I can follow the impedance as a function of frequency.

GUPTA: Can we go forward to the slide?

(Slide)

What we are trying to do is to measure the slope of this line.

(Slide)

Here is the real data, and we are trying to measure the slope of this line, the height of this circle here, the extrapolated semicircle, and looking at its diameter. If you go through the math – and I must say that I am not an expert at complex impedance so I would not be able to give you the equations here, but they are available – this diameter would be called the charge-transfer resistance. In other words, these have physical meaning as far as the cell is concerned, as long as you equate the cell to that equivalent circuit that I proposed, which is, admittedly, an oversimplification.

LACKNER: I guess what I'm trying to get at is what the physical meaning is of those curves?

GUPTA: I really cannot make any statements about that precisely, because I think that the equivalence of the cell to the equivalent circuit is a very tenuous assumption. Our purpose here is fairly limited. We really want to do an empirical correlation here.

If you want to make that assumption that the equivalents of the cell here to the equivalent circuit is good, then these parameters acquire physical meaning. For example, the height here is equivalent to the capacitance of the double layer. The diameter here is equivalent to resistance of charge transfer.

But it really will not be the case in the real cell because the equivalence itself is really not very good. We are really pleasantly surprised that it does show this type of behavior, which is roughly what we would expect.

LACKNER: The reason I find this interesting is in some of our tests with actual flight satellites, and on the ground-simulated satellites, we find that as they age and as they deteriorate, you get an increase in the internal resistance. Particularly, between charge and discharge, they can vary from 5 milliohms to 60 milliohms.

GUPTA: This is precisely the kind of properties we would like to measure. We are planning a test program, where we will cycle cells, flight-quality cells, and measure these as a function of sub f divided by 5, and sub f divided by 4, 3, 2, 1 and at failure, and we will see if there is any correlation.

We would also like to do other things. For example, we would like to take a cell to a certain state of charge, equilibrate and apply a pulsed current to it. Basically it is a charge efficiency measurement and we would like to see at what point of charging level there is an irreversibility, and whether this irreversibility is growing as a function of aging and so on.

So yes, answering your question, I think that it will show up in this type of an analysis.

LACKNER: Just one general observation I would like to make of the whole area of accelerated testing is, it appears we are doing accelerated testing on completed cells.

Now if you are in a procurement program for a satellite, by the time you have a completed cell it is pretty sad. You have to really have a good idea of what to specify for your cell and have accelerated programs on components, so you can sort of say yes, we know these components and how you put them together will give us good life.

Is there any program along that line?

GUPTA: Speaking only about the JPL program, yes, there is. There is a parallel investigation about components and cells.

BETZ: Do you have a comment?

LANDERS: Yes. Along those lines, Joe, there is a mechanical engineer in our shop named Dr. Fritz, and he is approaching things from the point of view of a mechanical engineer and is looking for possible mechanical means of failure of these things. He is coming up with some very interesting results which I hope will soon get into the literature.

One other thing, along the lines of the question that Sid Gross asked, and maybe others, there was an attempt made to look at the manufacturing data for the Crane program in terms of what is called pattern recognition techniques by Perrone and Company at Purdue.

This has been published. When I read that paper, I really didn't see that it told us a lot, but it did say one thing, and that is the low capacity cells are likely to fail first.

McDERMOTT: I have one comment on Joe Lackner's trying to find an accelerated test for components.

I think this is good if you keep in mind that the proof is in the pudding. When you put everything together, it is the system that is going to fail. In the failure modes that we have looked at, it is the interaction of the various components in the cell that ultimately leads to death. So you can't rely too much on simply testing one component and then trying to put it all together in a mathematical model. You can't rely on that solely. You have to get it all in that can with so much electrolyte and see how the system fails.

DYER: In the impedance work, I find it difficult to understand how you can pick up defects in a cell based on the measurements you are making. Warburg impedance and capacitance are very insensitive to the small defects you were talking about before. Do you have a plan here by which you can be sensitive to these defects?

GUPTA: I'm sorry if I gave the impression that we are looking for or trying to characterize defects using our nondestructive evaluation techniques. I want to emphasize that the NDE that we are trying to do involves a completely empirical approach right now. If we can come out of it with some physical-chemical characterization of the defects, that would be purely a bonus.

I don't think that the Warburg impedance and the reactance, etc., are going to tell us anything about defects. The most we are hoping for from the impedance measurements is that, for example, the Warburg impedance might change as the cell undergoes cycling.

For example, we find – this is very preliminary work and I didn't really want to present it – it undergoes some change as the cell undergoes cycling, but we don't know if that effect is real yet.

As far as the defects are concerned, we do have a test plan to characterize or understand what these defects are. This work will involve spectroscopy, that is, surface spectroscopy. For example, we would like to see if there are ions that are capable of multiple oxidation states since we find that electron interaction seems to be rate limiting. We would like to find out if we can identify or characterize these sites, for example, nickel<sup>+4</sup> or cadmium. Auger scanning, Auger spectroscopy, and perhaps resonance Raman spectroscopy may be carried out now that we have some ideas. In other words, we could not have done resonance Raman spectroscopy on these electrodes, not knowing anything about what the rate-limiting process is. For example, if it turned out that the rate-limiting processes causing failure are physical processes that have zero chemical order of reaction, then there would be no point in doing chemical characterization of the electrode surface.

But it appears as if the rate is transport controlled and the failure has been caused by interaction with electrons or ions. What is more, the model is zero order with respect to defects, which strongly indicates that the defects are on some surface. Therefore, it makes some sense to use surface spectroscopy on the cell components, and I wouldn't be surprised if some of the spectroscopic results correlate to failure.

DYER: I have a second comment then. Your data seems to show it is a transport-limited, low-activation-energy, time-independent process. And yet your model is a defect-growing process with time. I imagine it would also be a high-activation-energy process.

How could you reconcile these two?

GUPTA: We have a sequence of processes, ions being transported to the defect site, and in the defect site interacting with ions or electrons. The reaction of the defect site with electrons has high activation energy, but proceeds at a very much faster rate than the transport rate of the electrons and the ions to the defect site. In other words, although the reaction that causes degradation and failure is a chemical reaction, it is not rate limiting. So any time you monitor failure or degradation, you will be picking up the slowest rate, which is the transport process. In fact, in electrochemistry, often transport processes are rate limiting, no matter what electrode reaction is going on.

THIERFELDER: I want to comment on the suggestion Dr. Landers made using a 45-minute orbit instead of a 90-minute orbit. A lot of tests were run in three-hour orbits. When I compared the results of the three-hour orbit with the one-and-a-half-hour orbit, they were identical results.

GUPTA: This is what our results show. I think it is cycle-limited and not time-limited.

# APPROACH

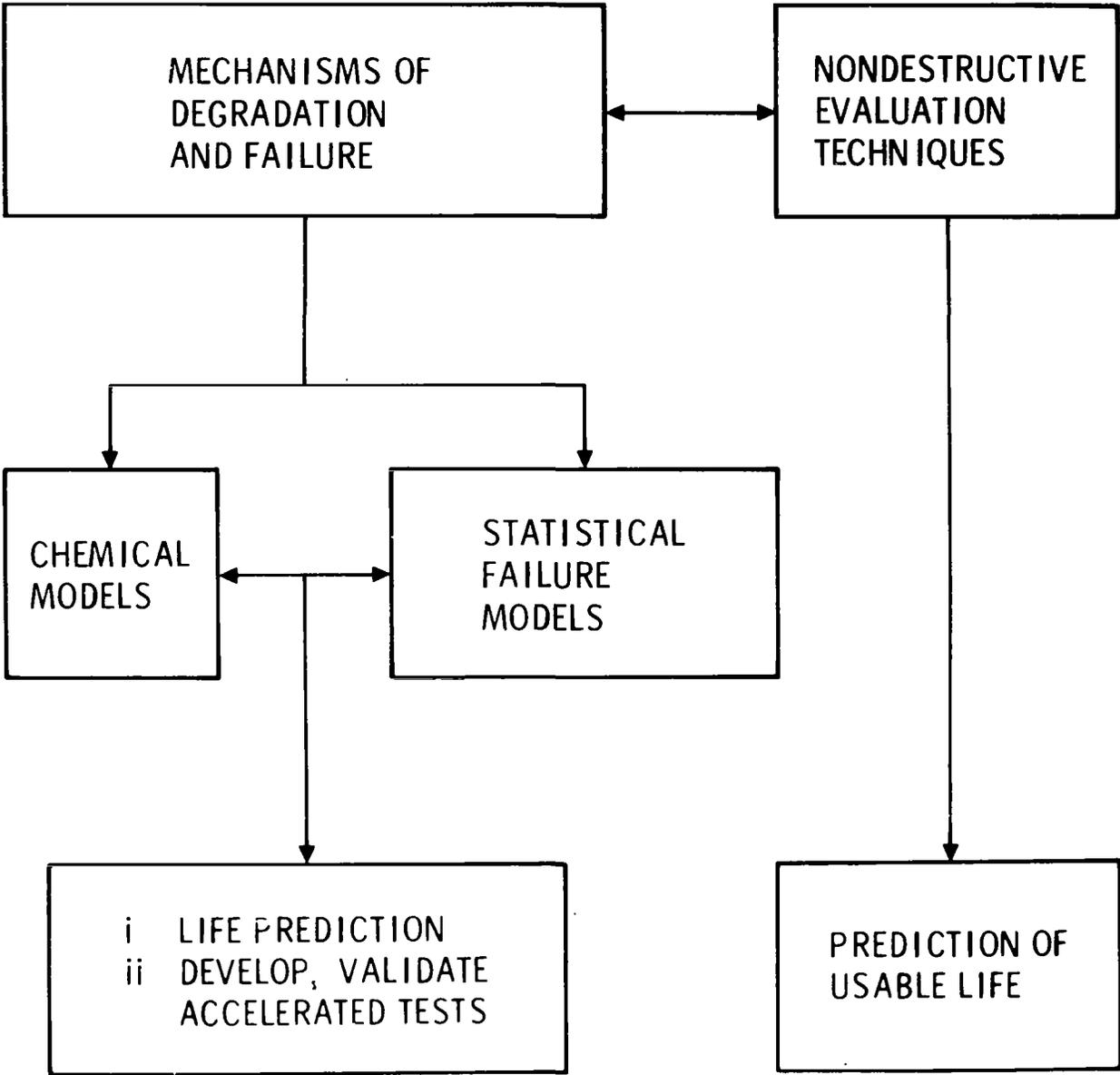


Figure 5-24

## DUAL APPROACH TO FAILURE MODELING

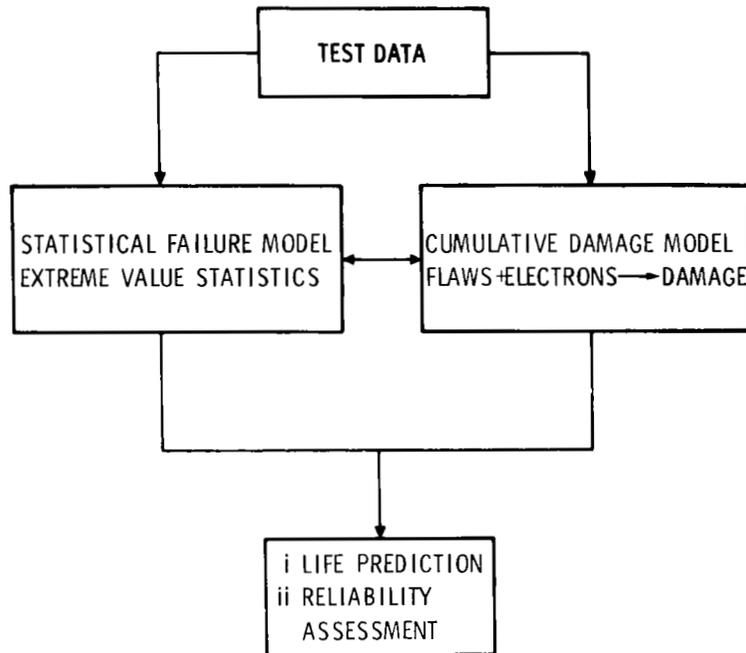


Figure 5-25

## QUASI CHEMICAL MODEL

FLAWS + ELECTRONS → DAMAGE

$$\frac{dc}{dn} = kf^m c^5$$

WHERE  $f$  = NUMBER OF FARADAYS OF ELECTRICITY PASSED

$c$  = AREA OF FLAWS

$$n - n_0 = \Delta n = \frac{1}{kf^m c_0^{s-1}} \left[ \frac{\Delta c}{c_0} - \frac{s}{2} \left( \frac{\Delta c}{c_0} \right)^2 + \frac{s(s+1)}{6} \left( \frac{\Delta c}{c_0} \right)^3 \dots \right]$$

$$c_f - c_0 = n_f k_0 (\text{DOD})^m c_0^m g^m e^{-\Delta E/RT}$$

WHERE  $c_0$  IS RELATED TO PLATE CAPACITY

$g$  IS RELATED TO CHARGE, DISCHARGE RATES

DOD IS DEPTH OF DISCHARGE

ASSUMPTION : FAILURE OCCURS WHEN  $c = c_f$

Figure 5-26

# DETERMINATION OF ACTIVATION ENERGY

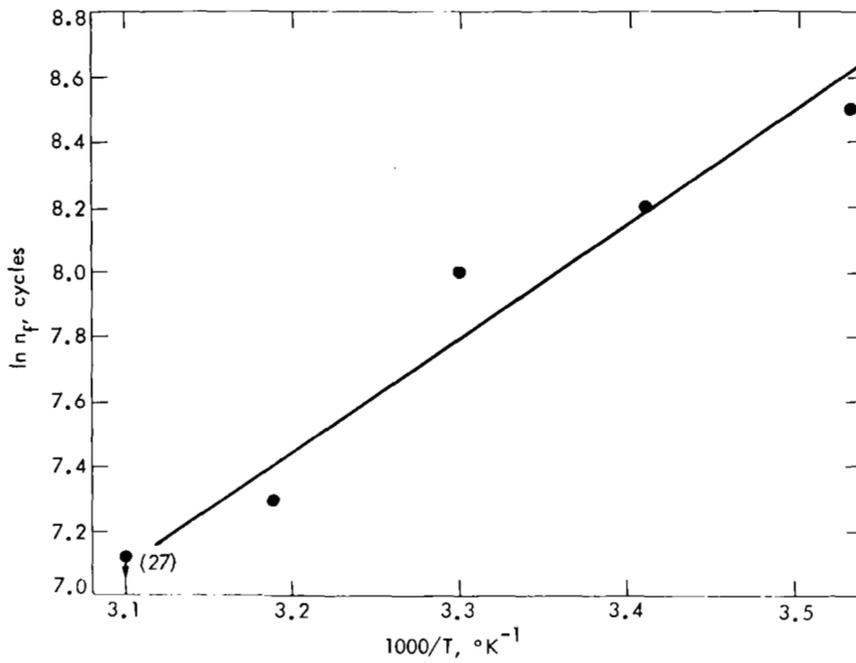


Figure 5-27

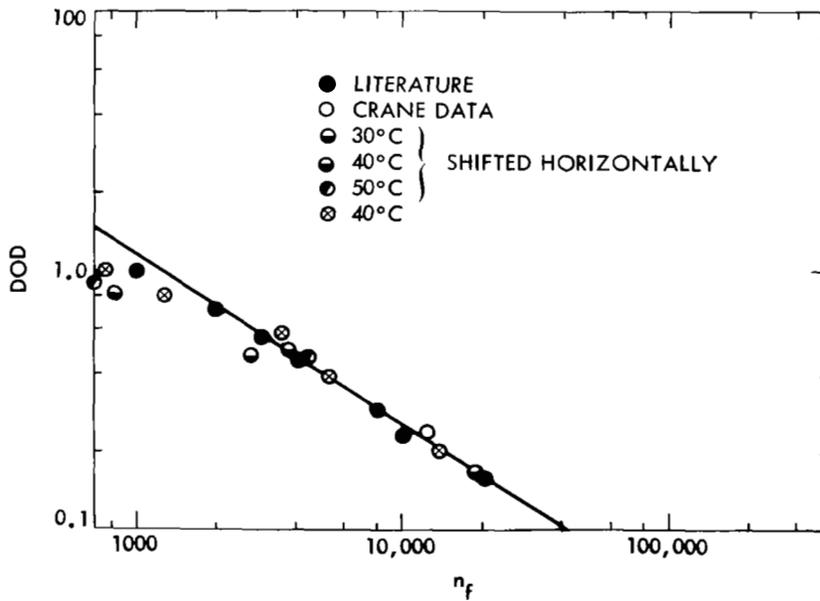


Figure 5-28

# STATISTICAL FAILURE MODELING

## WEIBULL DISTRIBUTION

$$f(c_0) = \beta (c_f - c_0)^{\beta-1}$$

$$\phi(c_0) = 1 - \exp \left[ - \left( \frac{c_f - c_0}{c_f - c_0^*} \right)^\beta \right]$$

$$\phi(n_f) = 1 - \exp \left[ - \frac{n_{f, \text{red}}}{n_{f, \text{red}}^*} \right]$$

$$\text{WHERE } n_{f, \text{red}} = n_f k_0 (\text{DOD})^m c_0^m g^m e^{-\Delta E/RT}$$

Figure 5-29

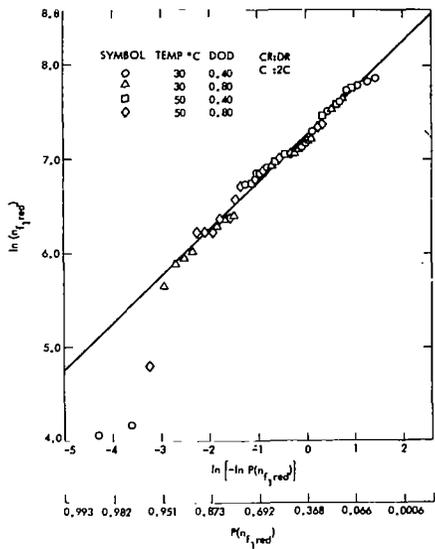


Figure 5-30

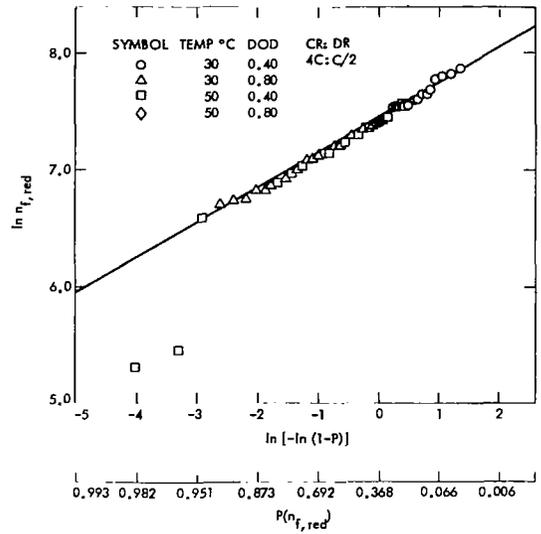


Figure 5-31

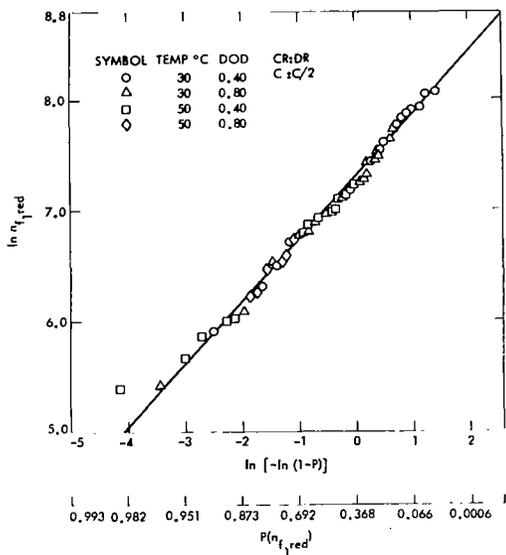


Figure 5-32

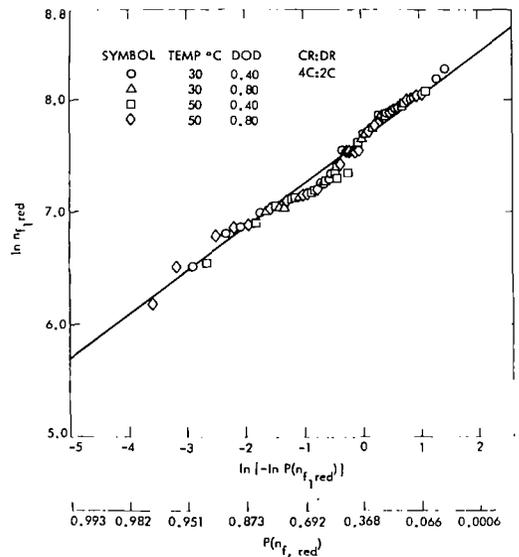


Figure 5-33

$$(N_{F, RED})_2 = (N_{F, RED})_1 (V_1/V_2)^{1/\beta}$$

WHERE  $(N_{F, RED})_1$  AND  $(N_{F, RED})_2$  ARE  
MOST PROBABLE REDUCED LIFETIMES FOR CELLS OF VOLUME  $V_1$  AND  
 $V_2$  RESPECTIVELY.

THIS TECHNIQUE THEREFORE CORRELATES CELL LIFE WITH CELL SIZE AND,  
IF VALIDATED, WILL ALLOW LIFE EXPECTANCY TO BE FACTORED INTO DESIGN OF  
POWER SUPPLY OF SPACECRAFTS.

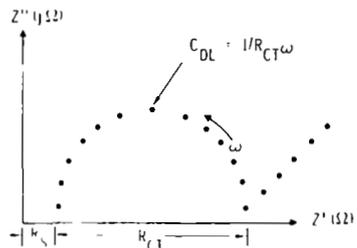
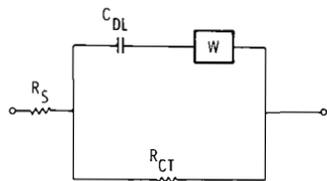


Figure 5-35

COMPLEX IMPEDANCE DIAGRAM

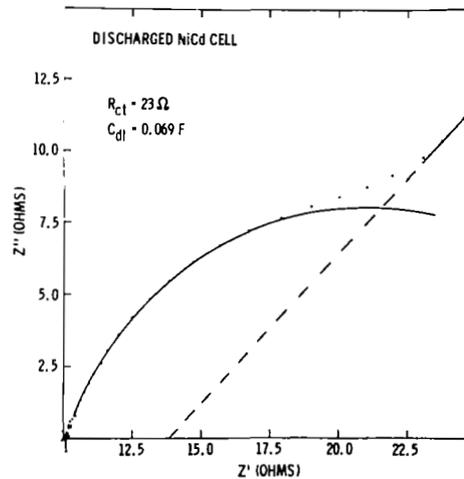


Figure 5-36

COMPLEX IMPEDANCE DIAGRAM

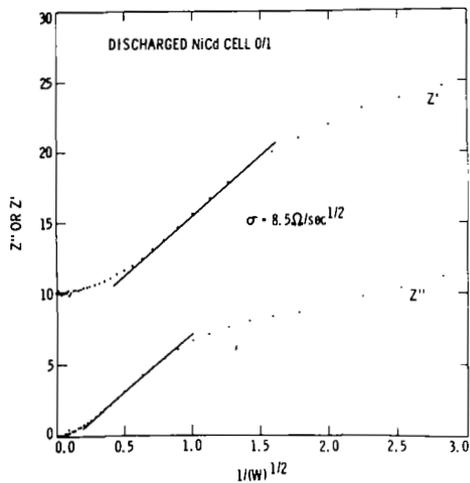


Figure 5-37

COMPLEX IMPEDANCE DIAGRAM

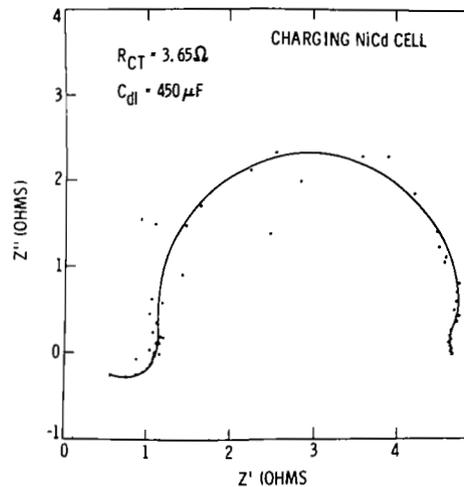


Figure 5-38



## MISSION SIMULATOR TEST DATA

E. Hendee  
Telesat-Canada

I am going to go back and get an overview of a real-time mission simulation test program which was performed in conjunction with our ANIK 1A2 satellites.

(Figure 5-39)

This is the overview of the test program up to the last eclipse season, but not including it. There were ten cells which underwent the mission simulation. We are rigorous on most of the characteristics within the test program. We simulate the temperature profiles, electrical profiles, etc. The only thing we did not simulate was the g loading on the cells, and of course the vacuum, which should not affect the system.

By eclipse seasons, the end of the maximum, end of discharge voltage per eclipse season is defined through here and through here for the test program cells.

Superimposed upon that by eclipse season would be the A1 and A2 satellite cell voltages.

(Figure 5-40)

On this one, rather than comparing the end of eclipse discharge voltages, maximum DOD voltages by eclipse season, I have done it from a date of activation. You will see there is a far better correlation on these with the exception of the very early part in there. There is an excellent correlation. And again, out until the very, very end.

Going to the first figure, you will notice that at this point the divergence between some cells. Following the fifth eclipse season, we put some of these cells on a continual slow charge. Our satellite did not have the capability for trickle charge. We had either fast charge, slow charge, or open circuit. Our nominal way of handling the cells was open-circuit storage with reconditioning every 30 days or thereabouts.

After the fifth eclipse season, some of the things we saw indicated that the test program to develop a backup mode of operation, we should put some of the cells on slow charge. Now this slow charge is about a C/30. It is pretty high.

And from this point on all the slow charge cells were put on 255 milliampere storage season charge complete with the reconditionings every 30 days.

Also, at this point, it would probably be best to look at the second figure. Following this season right at this point, we elected to go and do our reconditionings down to 1 volt as opposed to 1.139, which we had done the previous seasons. This would be on not only the battery test facility, but on the satellites as well.

You can notice a sharp increase in this cell and not in this cell.

This open-circuit storage cell increased fairly well. You will notice in the next eclipse season, going the way we would, we probably would have been down below 1 volt.

You will notice that the increase in the DOD for the reconditioning did not affect the slow charge storage cells that much.

Now, I am not going to go through all the seasons. I am just going to show the more interesting ones. The first few seasons up to the first five, even ten eclipse seasons were quite nominal. You have all seen them, and I would like to go to the next Vugraph.

(Figure 5-41)

From seasons 5 – well, seasons 1 through 10 you notice very, very little difference with the open circuit storage probably outperforming the slow-charge storage cell by a very, very little bit.

And then on day – I think it was 24 – we had an operator error, which limited the C/10 charge return to 32.5 percent on that day, and we topped it up with a slow charge. The total return was 130 percent.

You will notice that the open-circuit storage cell the following day (day 25), dropped way down. It had very little effect on the slow-charge storage cell, and this story starts to repeat itself on and on.

(Figure 5-42)

Now, we are up to season 12, and the slow-charge storage cell is showing very good performance. Cells are showing very good performance, and the open-circuit storage cell is decreasing.

One of the things we wanted to do is check to see if there is anything growing in there that we might be able to see if we were to torque the pack. We torqued the pack and this is a pack of seven cells, seven ampere-hour cells. The following day this is what happened: it recovered. It started to drift off again and recovered. We can see the intermittent going on in there.

(Figure 5-43)

Now, we are up to the next eclipse season. We are coming out, it is dropping down. At that point, I believe we are doing about 120-percent charge return. The slow-charge storage cell again doing beautifully. This one is not; therefore, we had to increase the charge return to 140 percent at the fast charge rate. That helped. Still started drifting off.

(Figure 5-44)

And on and on again. The open-circuit storage going quite intermittent to take a look at it. Slow-charge storage was doing very well.

Now this is a high slow-charge rate.

(Figure 5-45)

One of the things that I elected to do was see if this really was a definite short or just a charge exception of what was going on.

We varied the temperatures at the end of slow charge for the eclipse days. We noted the slow-charge cell responded as it should, as we would expect it to. But the open-circuit cells showed very, very little response to this, which to me means that there is a charge-limiting short developing in it, and we are clamping on the voltage.

(Figure 5-46)

This plot was experienced, I believe, up around eclipse 13, 14, and we have seen it ever since. This is on the slow-charge cell, and we can see a short coming in during the slow charge, and then tapering back off. It goes down, and this recurs between once every day to two days.

So there is indeed a short on the slow-charge cell as well. But it is only during charge, it is not once the cell is either discharged or open circuited.

(Figure 5-47)

Every so often we pulled out cells for chemical analysis, and this is destructive testing. Unfortunately, we are only down to two cells for the entire test population right now, which sort of limits some of the more recent evaluation that I have done. But, to take a look at the very first portions here, the very first data points, these are the baseline cells.

We had, unfortunately, three lots for three spacecraft interspersed. Most of them were lot 4 cells. Almost all these cells, in our mission simulation tests, were lot 4 cells. I think there were about three lot 2s, and I think one lot 3 or something like that.

The negative electrode flooded utilization, and you can see, if you will allow me just a bit of artistic impression in there, looks like it is leveling out at around 80 percent.

(Figure 5-48)

This one is the total free charge which, again, looks like it is having a tendency to level out at around 5 ampere-hours. We started with about 2.4 ampere-hours. It looks like it is settling at about 5.

(Figure 5-49)

The overcharge protection is decreasing similarly, and again we look at it together with utilization and precharge, etc. It will be coming out something like this.

(Figure 5-50)

This is again the carbon content of the cells; and even the trickle charge – what is interesting is that the trickle charge cell is not increasing that much. One of the things that probably this means is that the cell was kept at the same temperature, being driven at the same temperature. It was a pack that was not being charged, and therefore there was a very small temperature differential, and the charge itself was not affecting the buildup of the carbon, it was due to the temperature.

So the effects are basically due to temperature; the buildup of carbon would be probably temperature, and probably very little effect due to the charge rate.

(Figure 5-51)

One of the things that we noticed in our test facility is the extreme dropoffs and the intermittents shown before, and also seen to a certain degree on our satellites, would be the cadmium migration. And this is what we attribute.

You will notice the cadmium in the separator looks like it is probably leveling out. Cadmium in the positive is still going up. Whether it is leveling out at this point I don't know. I don't have enough points there. It looks like it may be.

(Figure 5-52)

The electrode pore volume for the positive electrode has stabilized out quite well. There is no doubt that that is going along pretty straightforward – this is total pore volume. In the negative electrode, however, the pore volume is increasing quite steadily.

(Figure 5-53)

This is a plot of the negative electrode expansions that we have seen. The upper zone, the lower zone – again, this is artistic impression to a degree. It does look, indeed, as if it were leveling out again at the end of the eleventh season.

(Figure 5-54)

This is the positive electrode expansion, upper and lower zones, and again it looks as if perhaps the expansion that we have seen had somehow limited itself. I am sure we can all hypothesize. There is a limited amount of space within the cell for things to expand there before we are up against it.

(Figure 5-55)

Now, here is the thing which gets back to impedance, etc. This is micropore volume.

You will notice that although the positive electrode volume started to level off as the total volume, the micropore volume has all of a sudden started to take off. I suggest that this is probably where the electrolyte is going. It is going into the micropore sites, and it is escaping from the separator, is drying the cell out and this is one of the problems we are having, why we are seeing impedance problems, etc. The negative electrode is more or less steady. I am not sure what that is.

These were 7-ampere hour cells. The one notable characteristic was that they had silver in the negative plates. They were typical 1971 General Electric manufacture.

## DISCUSSION

BETZ: I have a question for you. What kind of separators did you have in the cell?

HENDEE: That would be nylon.

BETZ: They were nylon separators?

HENDEE: Yes.

VASANTH: Kindly let us know whether the carbon content was increasing due to the cycling or the temperature had any effect?

HENDEE: The temperature – I should probably explain the temperature profile. This is a spinner satellite. The cells are pretty well on the outside of the satellite up against the solar panel. They very seldom go above about 74, 72°F.

Incidentally, I apologize, they are all in Fahrenheit, because this is how we started out. We didn't want to change in the middle of our program.

They are pretty well heat sumped to the deck. I would say that it would be that normally combining what we see in this data with that seen in other analyses, that it would be temperature, mainly temperature dependent and not charge dependent because we saw that the cell which was on continuous slow charge showed almost no increase in carbonate content over the cell which was in the open-circuit storage.

VASANTH: My second question is, did you analyze or did you have a chance to analyze the positive base for cadmium? Due to cadmium migration you could have, perhaps, cadmium deposited in the positive base?

HENDEE: I believe there was a part of that shown. I know I went through it a little bit fast.

VASANTH: Was the content of cadmium increasing due to cycling of the temperature in the positive plates?

HENDEE: Due to temperature?

VASANTH: Yes.

(Slide)

HENDEE: One of the other things, of course, that is probably indicative is that I believe — let me just go back through a detail plot here. I don't have it written down, but I was trying to see which one was the slow-charge cell and which one was the open-circuit cell.

You will notice that they are both living in the noise level of each other, and one was on continual relatively high-rate charge, the other one was open circuit, and it seemed to make very little difference.

The only thing I can say for the performance we have seen is that cadmium migration is probably going on in both cells, but it is in a different form in one cell. We have not analyzed it in detail as to the form between the slow-charge storage and the open-circuit storage.

McDERMOTT: I found your data toward the latter part, the quantification of the amount of pore volume increase in the micropore volume, very interesting.

I might suggest that the best way to find out where the electrolyte has gone is to soxhlet the electrodes separately and just test for OH.

The reason I have said that there has been some discussion over the years about where the electrolyte is going, and the discussion is centered about the increase in micropore volume in the positive plate is drawing the electrolyte into the positive plate.

This may be true when you have got the positive plate versus the hydrogen electrode and nickel hydrogen, but in the nickel-cadmium system I think it could be that the negative plate is as well or better a competitor for the electrolyte than the positive plate, and your increase of total pore volume I think would possibly support this.

We have found experimentally that more times than not the majority of electrolyte ends up in the negative plate after cycling than it does in the positive plate.

(Slide)

SEITZ: There is an increase of cadmium, and it is given in grams. I don't know if it is grams per cell. But if it is grams per cell, we are seeing an increase up to about 10 ampere-hours of cadmium in the positive electrode. Since it is a 7-ampere-hour cell, then there is a loss of perhaps as many as 10. That is what you are showing.

I don't know whether you have cadmium in there originally, whether any cadmium had been built in. But, can you comment on the amount of transfer?

HENDEE: There's the original right there. That's our baseline.

SEITZ: Then that still corresponds to an increase in the order of 8 ampere-hours.

HENDEE: 3 grams.

FOUGERE: About this increase of both positive and negative plates, you said it is about 14 to 15 percent. Could you explain why you have such an increase on the negative plates?

HENDEE: In what, now? Thickness? No, I do not. Do you?

FOUGERE: It is surprising.

HENDEE: These are just observations.

RITTERMAN: Just a comment about where the electrolyte goes when it leaves the separator. In TRW we found most of the electrolytes to go into the positive electrodes rather than the negative.

HENDEE: I think that is to a certain degree borne out by exercising the cells and putting them into a certain amount of overcharge, too.

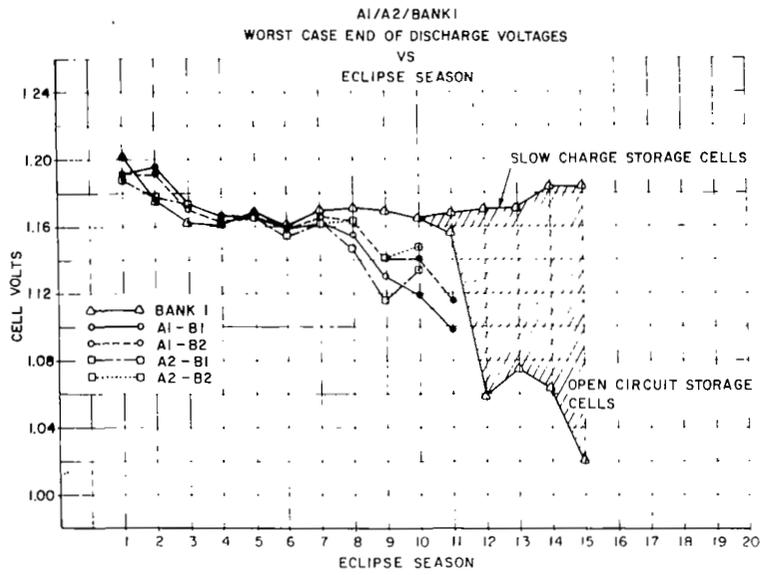


Figure 5-39

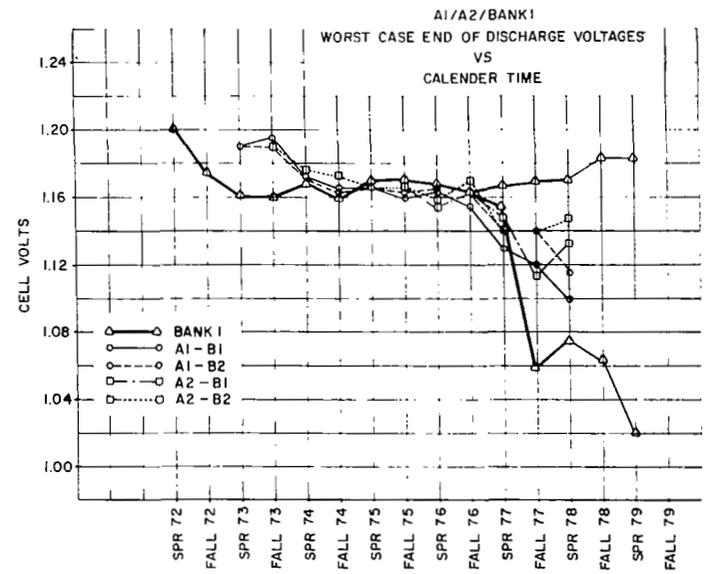


Figure 5-40

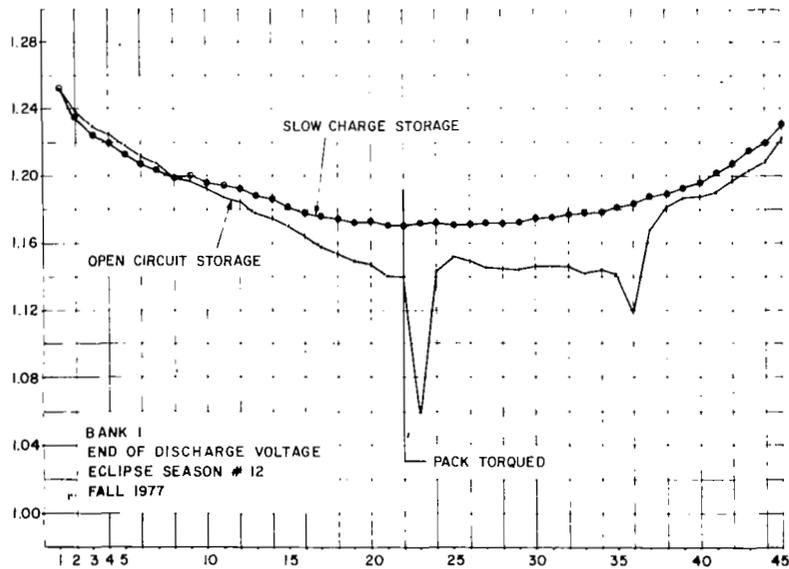


Figure 5-41

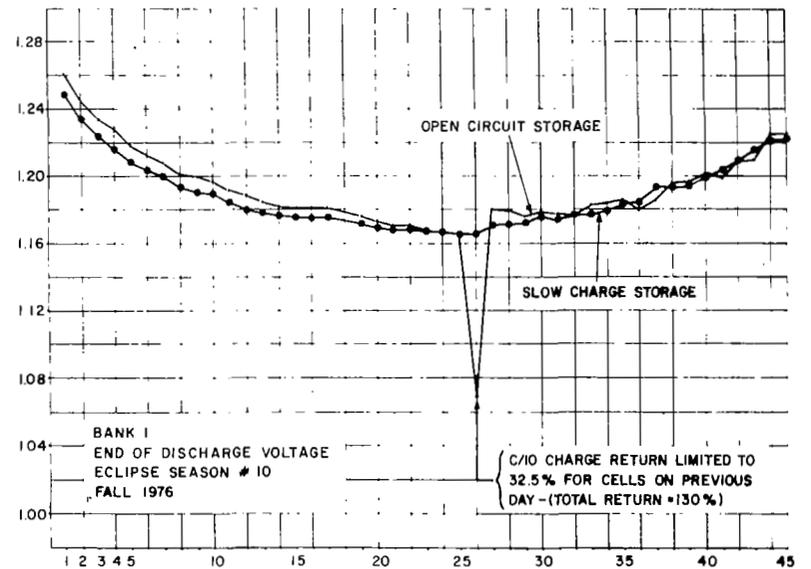


Figure 5-42

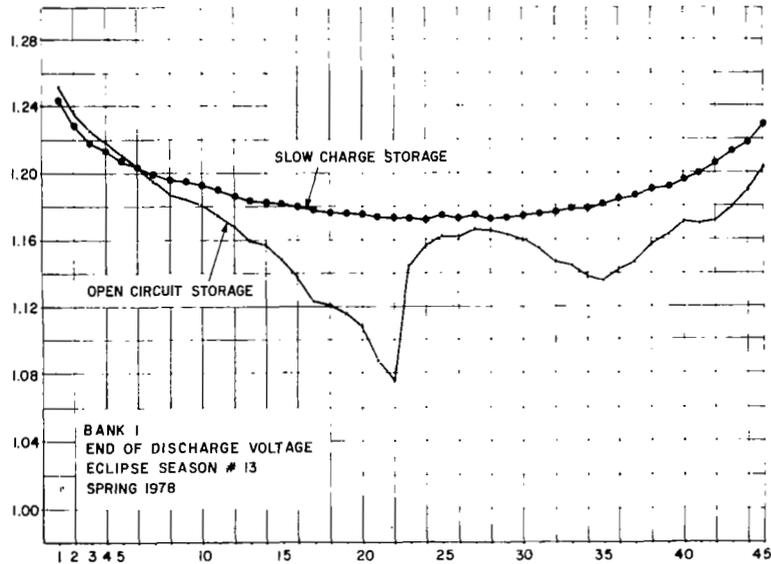


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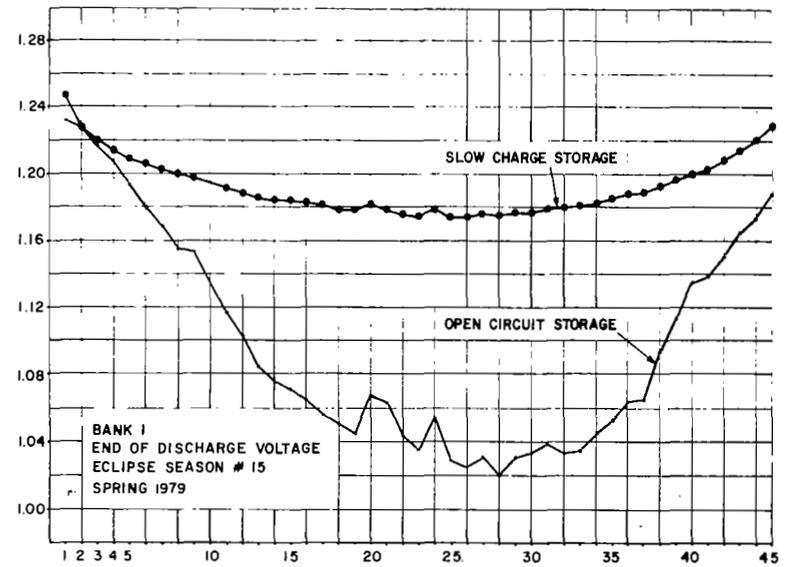


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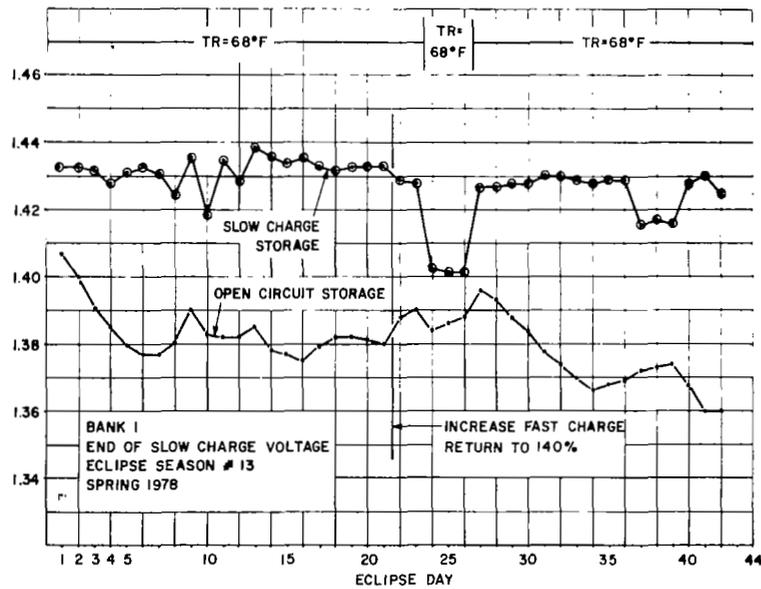


Figure 5-45

BANK I  
TYPICAL SHORT DURING SLOW CHARGE STORAGE  
CELL #2 (SLOW CHARGE CELL)

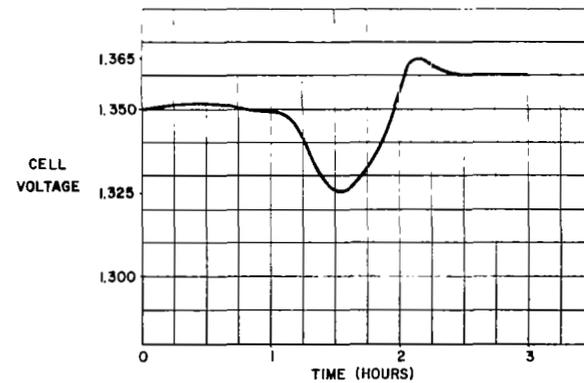


Figure 5-46

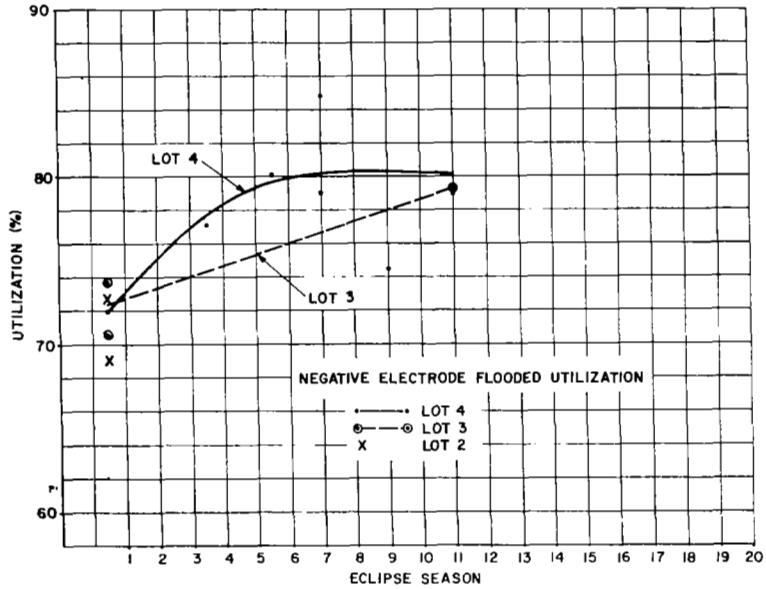


Figure 5-47

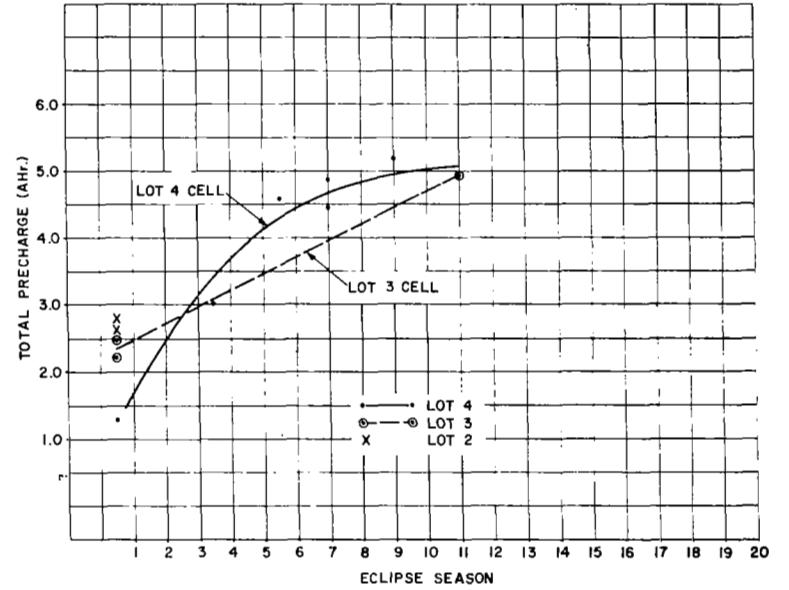


Figure 5-48

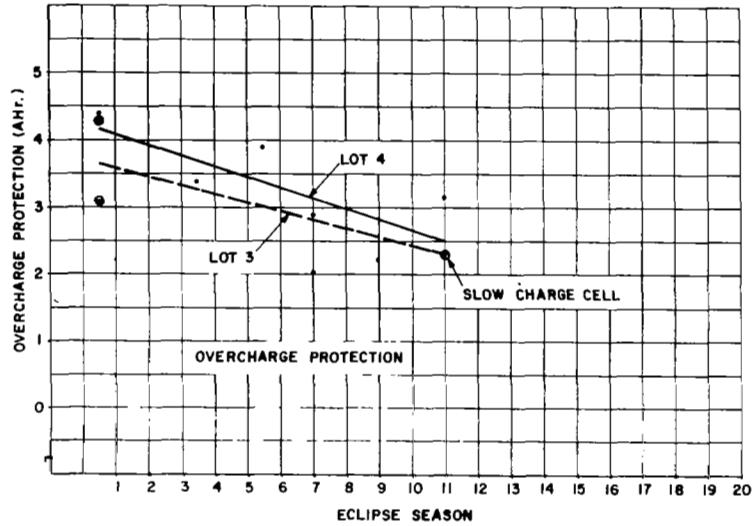


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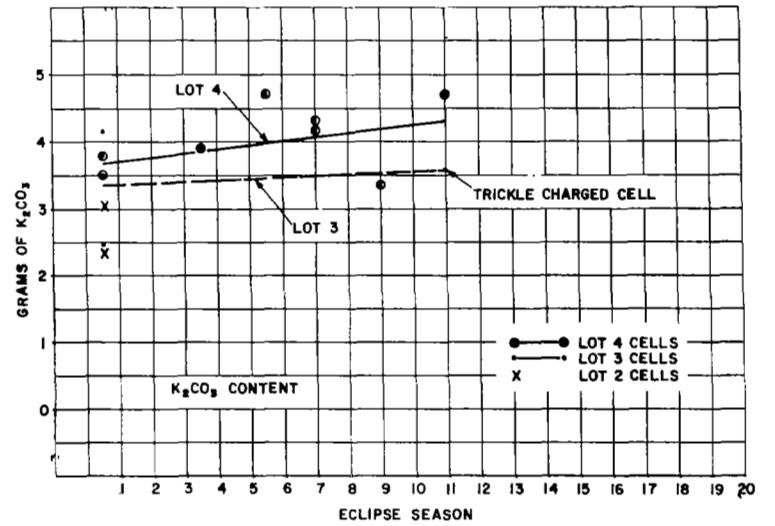


Figure 5-50

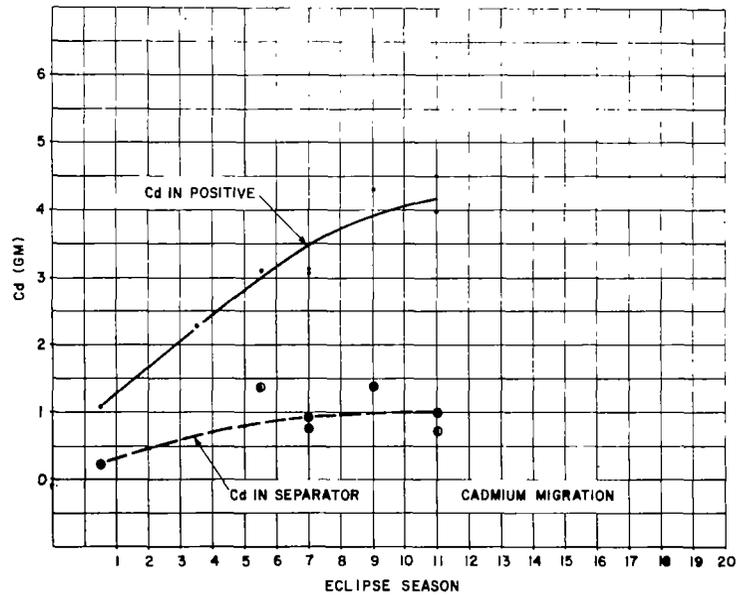


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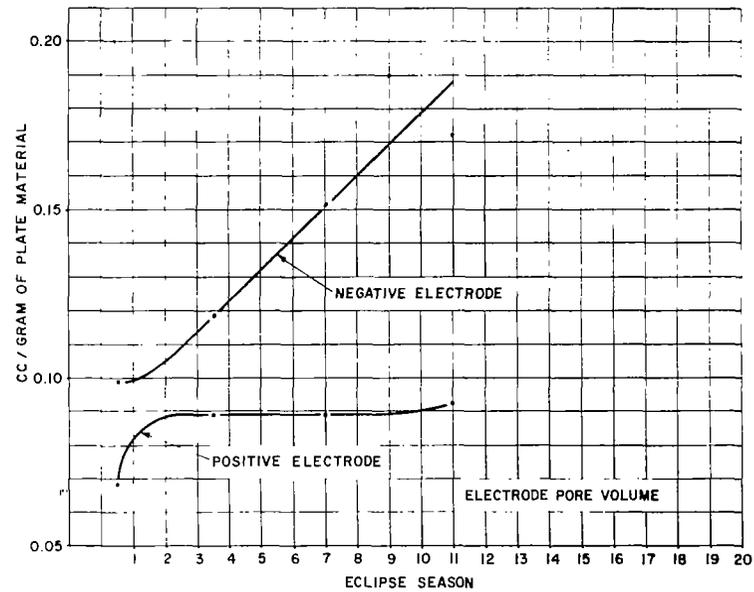


Figure 5-52

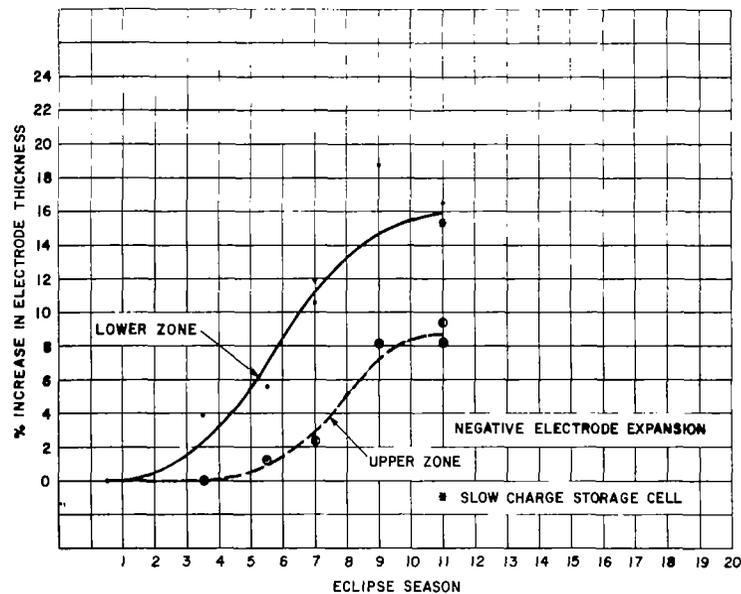


Figure 5-53

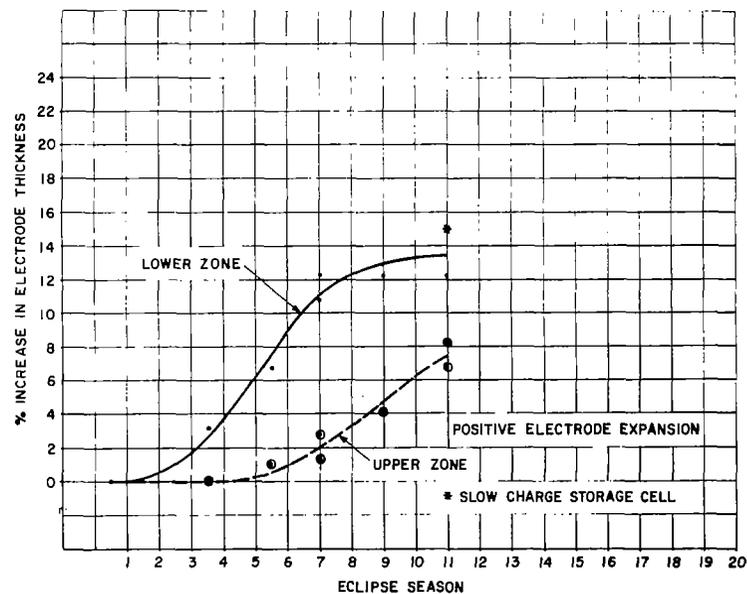


Figure 5-54

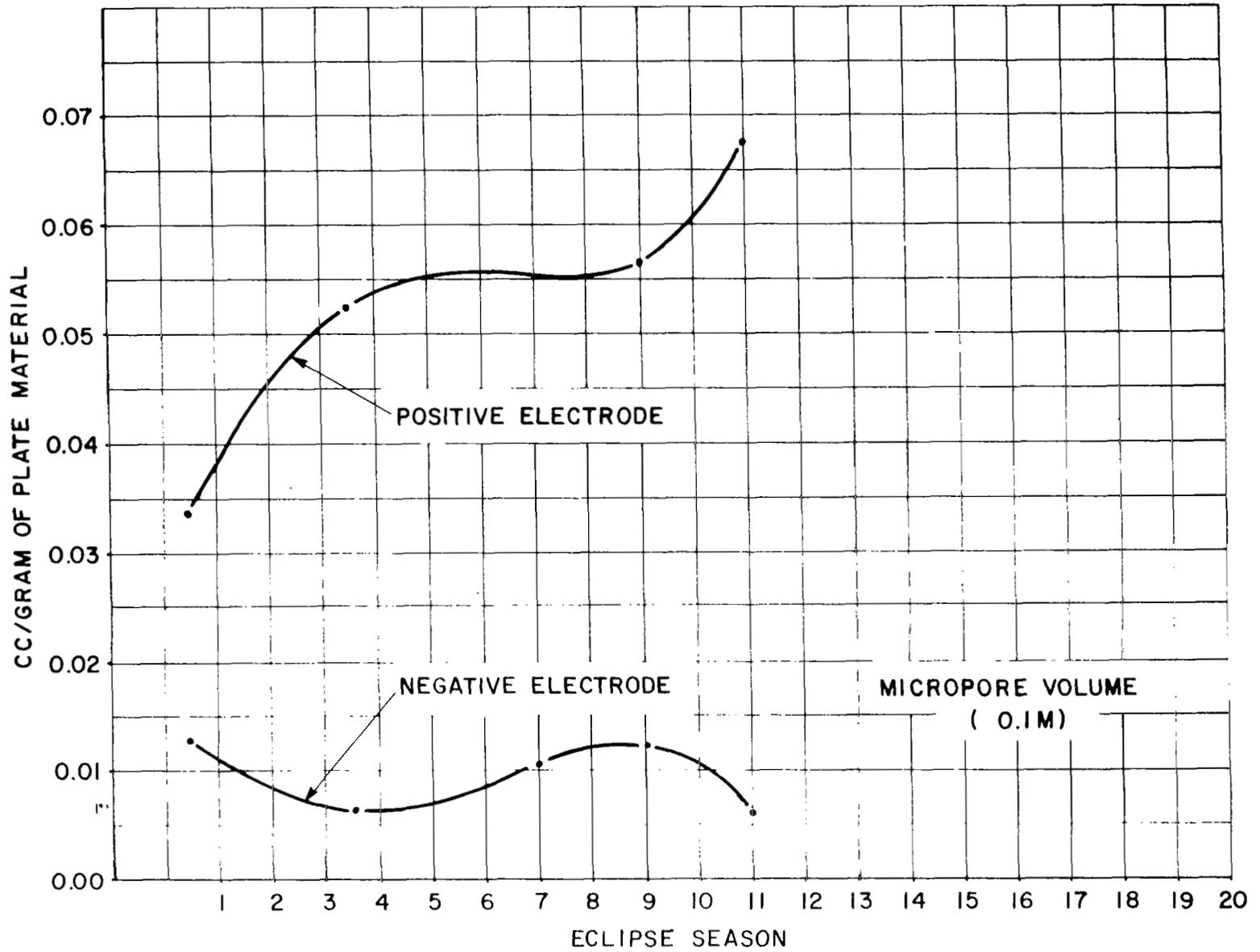


Figure 5-55

## ANALYTICAL MODELING OF BATTERY CYCLE LIFE

S. Gross  
Boeing

What I have attempted to do is look at the problem of battery cycle life from the standpoint of developing a simple analytical model that would be related to the physical and chemical processes that are involved in batter wear and failure.

The major assumption in this attempt was that in the cycling regime, cells will gradually lose capacity until the remaining capacity is depleted. And at that point the discharge cannot be supported.

For those cells which fail more abruptly, it is assumed that the processes which are severe in the degrading capacity are equally severe in the abrupt failures.

Furthermore, let's assume that the battery wearout consists of time-dependent chemical degradation and physical damage that is caused by cycling.

The model consists of a cell of unit capacity that is being discharged to a depth of discharge  $D$  when it is new, with a remaining capacity of  $1 - D$ . And the capacity loss that occurs during cycling is then  $1 - D$ , and that is equal to the chemical degradation loss which is time dependent,  $A$  times the number of cycles.  $N$  can be the number of cycles for cycle-based analysis, or  $T$  for time-based analysis for unit cycling time; plus the cycling degradation loss which is constant times the amount of discharge, the DOD times the number of cycles-to-failure which is the turnaround of the cell capacity.

Furthermore, it can be assumed that this coefficient  $B$  is dependent upon the DOD. It can be assumed to be some function of the DOD. I have assumed it is a possibility of being an exponential function and therefore entering into the coefficient on  $D$ , coefficient of  $M$ . For the case where it is not dependent on DOD,  $M$  would be simply one. And in that case, this term of one less  $D$  divided by  $D$  without the coefficient  $C$ , and  $B$  would be of course the group that Dr. Lander has been using.

(Figure 5-56)

To test this out, I have used the data that is readily available from Crane tests. This is the old data, not the accelerated life data, but the data many people have analyzed and reduced.

This data is shown here, this plotting cycle life against the DOD based on the rated capacity which is the top lines for each of the three temperatures. But for this analysis, we need the real capacity rather than rated capacity, and that has been worked to produce the lines just below, giving the real capacity. This is based on an assumption or based on an experience of a typical relationship between real initial capacity and rated capacity.

(Figure 5-57)

To check out this model, I have taken the Crane data. This is, of course, the 1.5-hour orbit data. The zero-degree data that was shown in the previous chart is given in red. This chart plots this function which has been fitted to match this data, the Crane data for variable exponents:  $N$  equal to 1 or 2.

And it would seem it doesn't make very much difference what  $N$  is, except in the areas of low depth of discharge and fairly deep depth of discharge rated at 90-percent range.

(Figure 5-58)

Now, assuming that  $M$  is equal to 2, we made the correlation for all three temperatures, and produced this type of chart. The thing we see is that the straight line, log DOD relationship that is often extrapolated on the Crane data or other test data, does not appear to hold in this kind of correlation.

We have a falling over on both the low DOD and the deep DOD side. For the case of  $N$  equals 1, it would be less of a fallover. In the case of  $A$  equals zero, this of course goes up to infinity.

(Figure 5-59)

The next question then comes up, what is the effect of temperature?

Taking the first chart on Crane cycle-life data and cross plotting it, we get cycle life as a function of temperature plotted linearly for two depths of discharge, 0.2 and 0.5, 20 percent and 50 percent.

Unfortunately, we have only three data points, only three temperatures, so we can't get a very good curve, but the two things that are apparent when you look at it more carefully is that the slope from zero to 25 differs as a function of the DOD. This slope does not equal that slope. And secondly, there is a change in slope at the higher temperatures, 25 to 40 degrees.

(Figure 5-60)

Now, when we plot the coefficients,  $A$  and  $B$  on an Arrhenius type plot, coefficients against reciprocal temperatures, again we see the same discontinuity in slope. This is the curve for  $A$ .  $A$  is the coefficient in the equation.

(Figure 5-61)

We have the same thing for  $B$ , also a discontinuity in the slope at the higher temperatures.

These last three charts all show that at the high temperature the degradation processes are occurring at a rate which is faster than would be determined by an Arrhenius type dependence, and certainly, it is not linear in temperature.

This means there are different degradation processes occurring at the high temperature, or at least occurring at a significantly higher rate than we have with the low temperature.

So, as far as old Crane data is concerned, it would not be valid to do accelerating tests at high temperature without taking this into account.

## DISCUSSION

RITTERMAN: You showed some very early failures at the very high DOD, almost close to zero cycles at 100-percent DOD, if I read that correctly?

GROSS: Yes. That was what the analytical model predicts.

RITTERMAN: That is the model. It wasn't in actuality?

GROSS: No, the actuality is fitted only to the limited DOD range, roughly 20- to 50-percent DOD.

RITTERMAN: How would you define failure?

GROSS: Failure in this case is defined the same way it was defined for the Crane tests where the data came from. For those tests it was defined as failure to provide 1.0 volt or failure to deliver a specified amount of capacity.

RITTERMAN: Was that 100-percent DOD, or you are bound to fail?

GROSS: The model predicts that at any time you are discharging, you are wearing something out. If you have 100-percent DOD and one cycle, but that one cycle did enough wearout so that in attempt to have cycle 2, you cannot quite make 100 percent.

Now, in actual practice, there is a small amount of cycle improvement the first few cycles, and it would not be valid for those first few cycles because that's a second-order effect. That is not taken into account in the first few cycles.

RITTERMAN: The problem I am having is with the definition of failure. I think it would be more applicable to define it as a cell short or a severe failure in capacity.

GROSS: I have defined a cell failure as the inability to provide capacity required to maintain a prescribed DOD.

Secondly, I have further assumed for those failures which are premature, the early shorting failures (failures which happen fast and are included in some of the Crane data), that the same kind of stress that caused capacity degradation also caused the early failures. As you know, the Crane data is the average of a large number of points.

MAURER: Sid, I think your last vugraph shows some of the dangers one can get into in extrapolating the data base beyond the range of the base. For example, in talks we heard this morning, the first three talks gave valid projections within that range.

But, if you would try to take those equations and extrapolate to geosynchronous conditions, for example, where we know that that equation would give a false indication of life, we would be predicting lifetimes of many tens of years. And we know that the lifetimes of those are shorter.

What you are doing is picking up the low activation energies first, and as you go to higher temperatures, you pick up higher activation energies. So that the lower part of your curve might be the mass transport mechanism that was discussed earlier this morning.

And the lesser part of your curve, where the higher temperatures are, would be into the higher activation energies as chemical reactions like nylon degradation which was taking place around 15 kilocalories in the tests that we have seen.

GROSS: I think there is no question about that. I think also there is no question that even though for some cycling conditions, time dependent processes are not large, they cannot be ignored and that an equation should be introduced. So, especially when you try to extrapolate them beyond a small amount of data, you at least have that parameter.

HAFEN: Sid, I would like to know if these failures were pack failures or individual cell failures. If they were pack failures, did you make an attempt to somehow correlate the individual ones?

GROSS: They were average cell failures of all of the cells. A pack failure would be the failure of the last cell in the pack. And this is the failure, average failure of the individual cells.

HAFEN: In other words, you take the cycle numbers and you divide them by the number of failures?

GROSS: What essentially is done is, the cycle life of an individual cell – of individual cells – is plotted on a curve and you get a distribution, and you fit that distribution as well as you can, with, in this case only three lines; one line for each temperature.

VASANTH: Would it be possible to predict from your data any particular type of specific type of degradation process that will be taking place?

GROSS: If there had been more data points, more temperature data points than three, then it would have been possible to make some kind of estimates of the activation energy. But you just can't plot any, make any prediction on three points. You don't have enough data to draw curves that would give you the intersection that you need to get your activation action.

HALPERT: I did want to clarify a point that came up earlier in this morning's presentation by John Lander, who said manufacturers had a lot of flexibility.

I did talk with John afterwards and with Ami Gupta, and the comment we tried to make is that the flexibility a manufacturer has is within the range of electrolyte volume and concentration, that's all.

Secondly, in that regard, Ami Gupta had indicated the reason he was able to get some of the results he did get was because this particular lot of cells was very uniform.

As a matter of fact, a group of those flew in one of our spacecraft, the AE spacecraft, and it was also in three additional packs at Crane, the numbers of which I don't have at hand at the moment.

So he would not have been able to get this data without the uniformity of the packs. We don't want you to jump to any conclusions about flexibility in the manufacturing process.

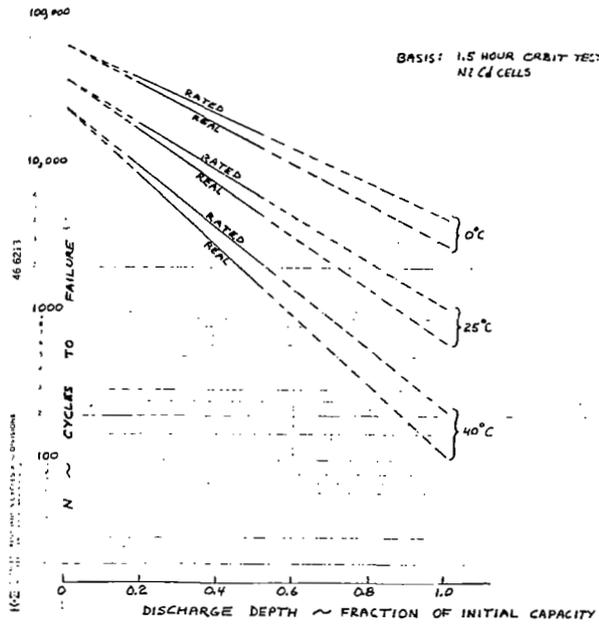


Figure 5-56

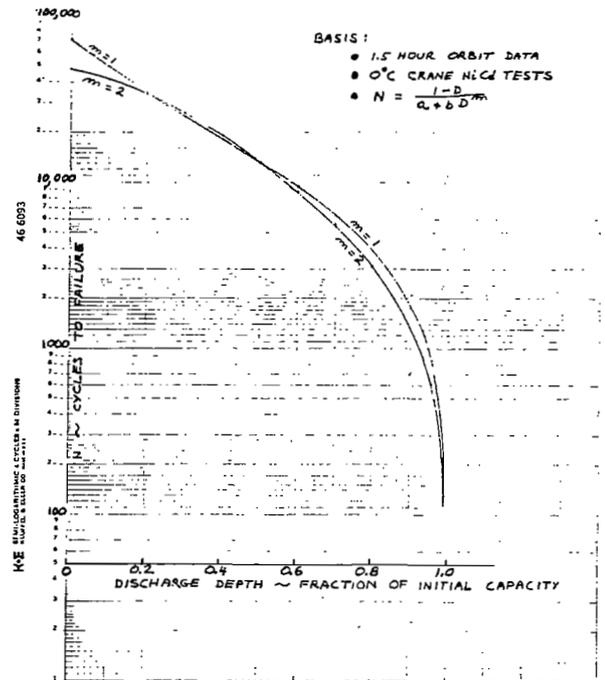


Figure 5-57

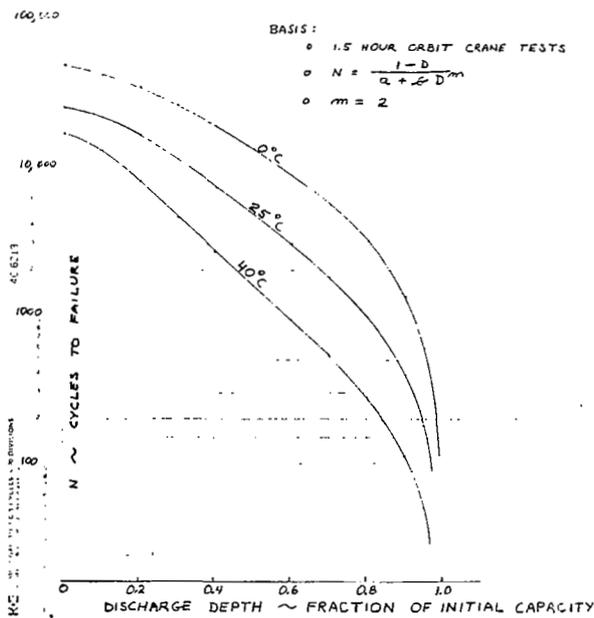


Figure 5-58

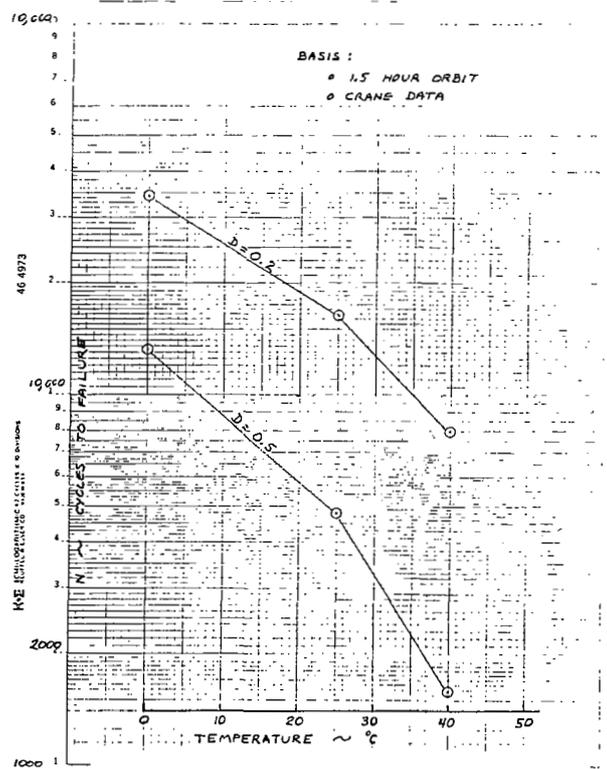


Figure 5-59

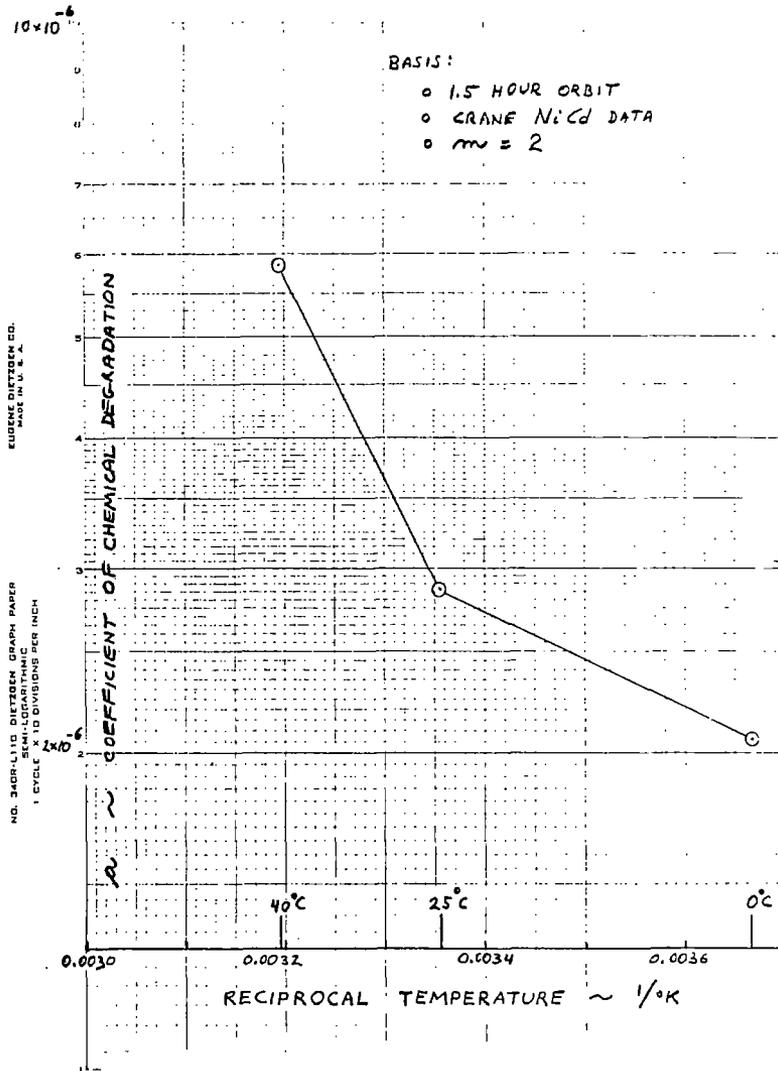


Figure 5-60

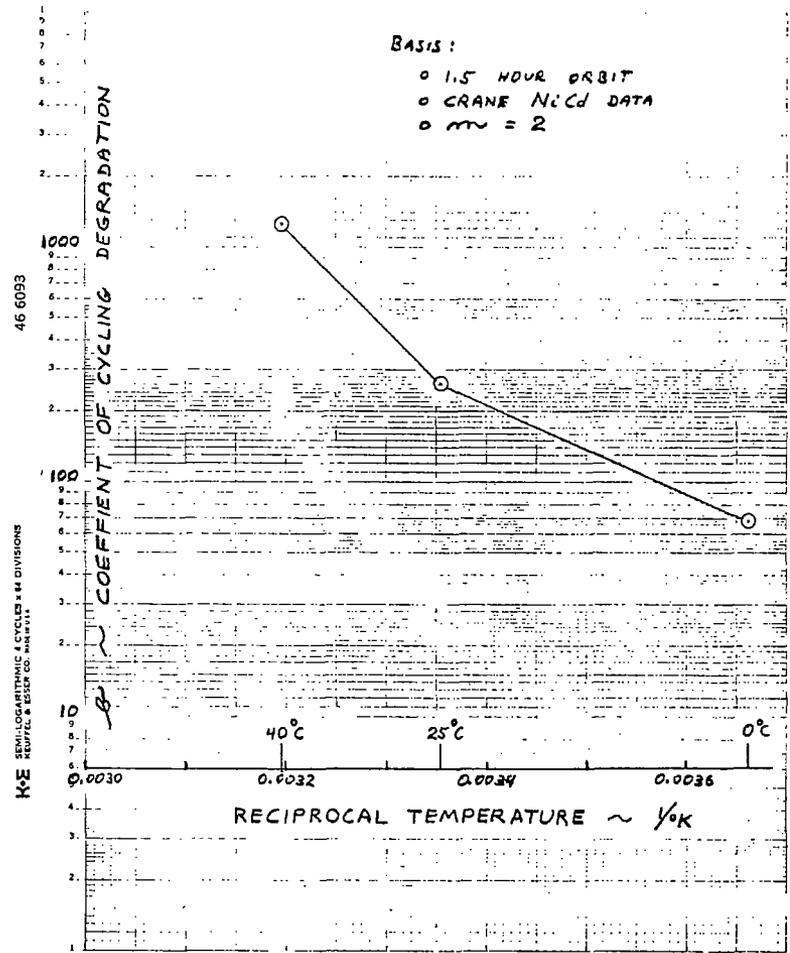


Figure 5-61



## THE PRACTICAL LIMIT OF LOADING NICKEL HYDROXIDE ELECTRODES

E. McHenry  
Bell Laboratories

This is a presentation of a previously unreported investigation of the practical limit of loading nickel hydroxide electrodes.

Originally, I had intended to study the effect of compression on the positive electrodes. It is presumed that as you compress the electrode, you would restrict the size of the pores; you would develop an IR path, the electrolyte would not be able to get into the inside pores, and then the efficiency of the electrode would drop off. All the electrodes I used here were 1 inch by 2 1/4 inch by 28 mils thick.

(Figure 5-62)

It shows here originally on the unimpregnated plaque as it was compressed with very little compression, there was considerable distortion, until finally it collapsed all the pore structure and now the compression is trying to collapse the particles themselves.

You see a similar thing in the electrode which is loaded with nickel hydroxide. But we reach this plateau at a smaller amount of thickness. It runs into this problem as you compress a very low amount, because you have more material in there.

(Figure 5-63)

The most striking thing is that you can compress it up to 20,000 kilograms per square centimeter which is very close to the yield point of low carbon. You find that there is no real change in capacity: no loss. As a matter of fact, the capacity is better, so apparently there are not pores in the nickel hydroxide electrodes while it is running.

These were all done while they were wet, full of electrolyte, and they were compressed without drying. So that the actual working nickel hydroxide apparently is much more voluminous than nickel hydroxide is dried. Apparently, it is hydrated, and the hydrogen ions apparently just migrate right through the active material itself. They don't appear to need any electrolyte path to get inside the electrodes.

At that compression there certainly couldn't be any — there could be a few blind pores, but no continuous pores to the outside, or the electrolyte would leak out through them.

(Figure 5-64)

This is just a group of electrodes which were impregnated to different numbers of cycles, different loadings. As you compress the electrode, you will find at very low loadings that if you

measure the volume of the electrode, you subtract out the nickel volume, then you have the volume of nickel hydroxide left over, and calculate a density of nickel hydroxide in the right-hand column that's left in this volume after compression.

At very low loadings it is a little bit low. But this is explained by the fact that the nickel itself cannot be totally compressed. Unless you have enough nickel hydroxide to fill all the little pores in the nickel when you compress it, you won't get a good value. But as you get up about three cycles, you find that you end up with about 1.6 or very close to that as the density of nickel hydroxide in all of these.

A couple of the ones, say ten impregnation cycles was a little low, nine, but I had a considerable amount of shedding from these on forming, and this would be explained by the fact that when you have the shedding, some of the nickel metal falls off, too. So you get an erroneous result. Especially the last; we had a very low result, but we have none that are higher than 1.6, really. We don't have any 1.9s, or anything like that.

So it suggests that the nickel hydroxide — the density of the actual working material when it is wet and is hydrated and whatever — probably has potassium in it and everything else, that comes to about 1.6.

(Figure 5-65)

I have done the same in the early days of electrochemical impregnation. It was done at room temperature and all, so it is not exactly the same thing that we are doing now. But we end up with the same results; that the nickel hydroxide is in there working at about 1.6 grams per cubic centimeter.

(Figure 5-66)

This is reprinted from some work that Puglisi presented in 1976 at this workshop. And we see that this percent utilization as a function of loading level shows a very sharp break at 1.6, which indicates that yes, indeed, there is something about this kind of loading. If you load at higher than that, which you can do, vacuum impregnation, you are loading in nickel hydroxide with a density of approximately 3.6.

It will go in there, but when you try to work the material, it will either not work and give you poor utilization, or if it actually is activated, it tends to swell up and the plate expands until the nickel hydroxide that is there is now 1.6 again.

This was all done at room temperature, so I have no idea as to what happens at higher or lower temperatures. If this is actually a hydrated nickel hydroxide and has four waters or six waters or something of hydration, at lower temperatures it might have a different structure, such as eight waters or two waters; or at high temperature it might. If this were done at higher or lower temperature, you might find the density is different.

This is all I have, but it is very straightforward and simple, it indicates that actual working nickel hydroxide is only 1.6 grams per cubic centimeter.

## DISCUSSION

ROGERS: I don't know if I understand this correctly, but it would seem that when you compress the electrodes, you get down to a point where you cannot get ion flow through the electrolyte.

McHENRY: No. I presume in a porous electrode, in the very beginning, that you would need some way for the ions to get into the active material to make it function. And as you compress the electrode, you shut these pores down and you would find that your capacity fell off. But, in fact, it did not happen.

ROGERS: I don't quite agree with that. I think as you compress, you get very tiny pores where your capillary forces oppose your compression, and you would have, admittedly extremely small pores. But I would think they would remain open.

McHENRY: Well, what it came to was 32,000 pounds per square inch.

ROGERS: *Pretty small holes.*

McHENRY: You would think it would have some effect. You wouldn't think the capacity would increase. How small does the pore have to be?

ROGERS: *It would be hard to estimate quantitatively.*

DUNLOP: Do you conclude from this that you should compress your electrodes – when you get done you should lower them and compress them?

McHENRY: No, I am not suggesting you should do that.

DUNLOP: Why wouldn't you, though, based on the results? Why wouldn't you just compress your electrodes down? That way you would have an electrode structure when you are all done which is basically as thin as you are going to make it, and it is not going to change your performance.

McHENRY: I am not sure what would happen after many cycles. It might have an effect on the strength. As you compress them, you are going to bend all the little contact points, and will put a stress on them. Possibly they will corrode faster.

DUNLOP: I thought we could compress from the plaque – I thought you could compress without doing much damage to them.

McHENRY: I don't know. I have never run them for any length of time. I am not suggesting this is a way to make them. I am suggesting you cannot fit more than 1.6 grams per cubic centimeter in there and have it function well without swelling.

SLIFER: I have a question about the compression. You didn't mention anything about polarization.

Did you have an increase of polarization when you compressed in the electrode during the discharge of the positive electrode when they were very compressed and essentially had no voids? What polarization did you have?

McHENRY: I didn't measure this accurately, but there was no obvious change in the voltage, discharge, and charge voltages.

SLIFER: In the discharge voltages?

McHENRY: I didn't really look close into that. I was more interested in the capacity. But there might have been some, but not marked.

RITTERMAN: This is sort of a corollary to Dr. Slifer's question. But I would suspect that the compression might have decreased the surface area and resulted in an increase in overload or polarization.

Did you look into the effects of the active surface area after that?

McHENRY: No, I didn't. I just looked at the volume.

RITTERMAN: Again, you did not notice any sort of change in voltage or loss of capacity at a high current of discharge?

McHENRY: No. I was running these things at 200 milliamperes, 230-milliamperere hour electrodes. So I am running about the C rate. I didn't see any noticeable change. I didn't really measure and study the thing to make sure. But it wasn't obvious anyway.

GROSS: The density of charge and discharge in nickel epoxy hydroxide is different, so you can expect volumetric changes in that material, which of course has been observed. Now, you compressed yours in the discharge state?

McHENRY: In the charge state.

GROSS: Oh, in the charge state. So when you discharged then, you had a shrinkage?

McHENRY: I imagine that was true. But I think Dean disagrees with it. Apparently some of the data he has suggests that it expands as you are discharging. I had always thought it expands in the charging. But possibly that is not true. Maybe it is more voluminous in the discharge state.

GROSS: If you discharged it and it swelled, since you had essentially no void volume in it, the plate either would have to expand or you would be unable to discharge it.

McHENRY: They did show a little bit of springback on cycling.

(Slide)

After cycling, it did spring back a little bit. That was after about 10 or 15 cycles on this particular electrode. So it is possible that it is a little bigger when discharged. Maybe Dean is seeing a temperature effect.

LANDER: In partial answer to Jim Dunlop's question, on a program we had a few years back, we said "why don't we compress these positive electrodes and thereby gain some volume advantage and maybe a little bit of weight advantage." And we did. After a few cycles, they sprung right back to where they were, so it didn't make any difference anyway.

FOUGERE: Have you run many cycles on such compressed plates to determine the mechanical diameter after many cycles? Is it still rigid plates?

McHENRY: Yes. I have run them about 50 cycles after compression, and they still remain in one piece. They don't fall apart or anything like that.

FOUGERE: They don't perform or make any vibration or something like that on the plates?

McHENRY: No. They seem in good shape. No apparent difficulties.

GASTON: What happens now if I add some antipolar matter to the active material?

McHENRY: I didn't do that at all, so I have no idea what happened there.

SCOTT: I would like to ask John Lander what the volumetric loading was of those plates that he saw expand after he compressed them?

LANDER: I cannot give you anything but an off-the-top-of-the-skull answer there, because I don't remember the data that well, but I think it was more or less a standard loading for aircraft, standard plates which we were working on.

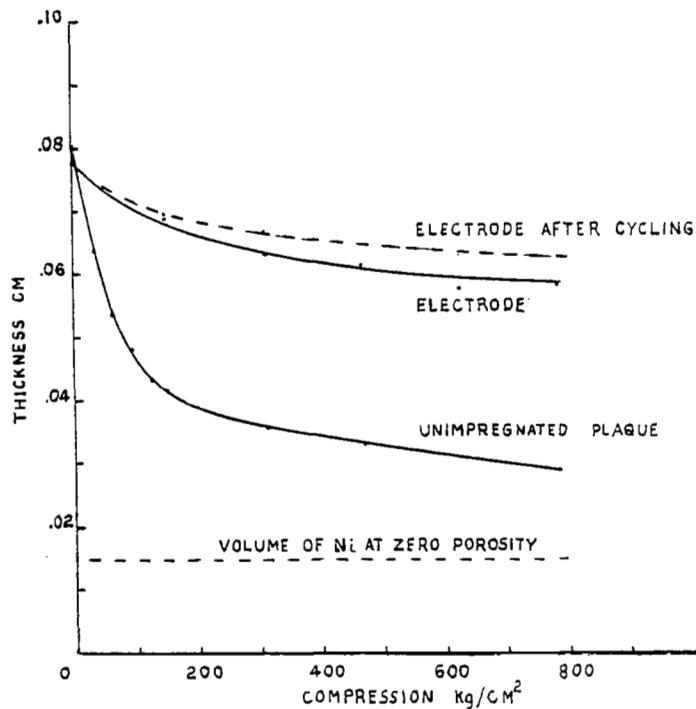


Figure 5-62

TABLE I

## COMPRESSION OF ELECTRODE #2241

Uncompressed	
Weight Ni(OH) <sub>2</sub>	0.7402 g
Weight Ni Substrate	1.6554 g
Thickness	0.0798 cm
Theo. Cap.	0.214 Ah
Meas. Cap.	0.173 Ah
After 780 kg/cm <sup>2</sup> Compression	
Thickness	0.0490 cm
After 6 (charge-discharge) Cycles	
Thickness	0.0528 cm
Capacity	0.190 Ah
After Second 780 kg/cm <sup>2</sup> Compression	
Thickness	0.0480 cm
After 12 Cycles	
Thickness	0.0528 cm
Capacity	0.225 Ah
After 2000 kg/cm <sup>2</sup> Compression	
Thickness	0.0404 cm
After 18 Cycles	
Thickness	0.0483 cm
Capacity	0.233 Ah

Figure 5-63

TABLE II  
COMPRESSION OF VACUUM IMPREGNATED ELECTRODES

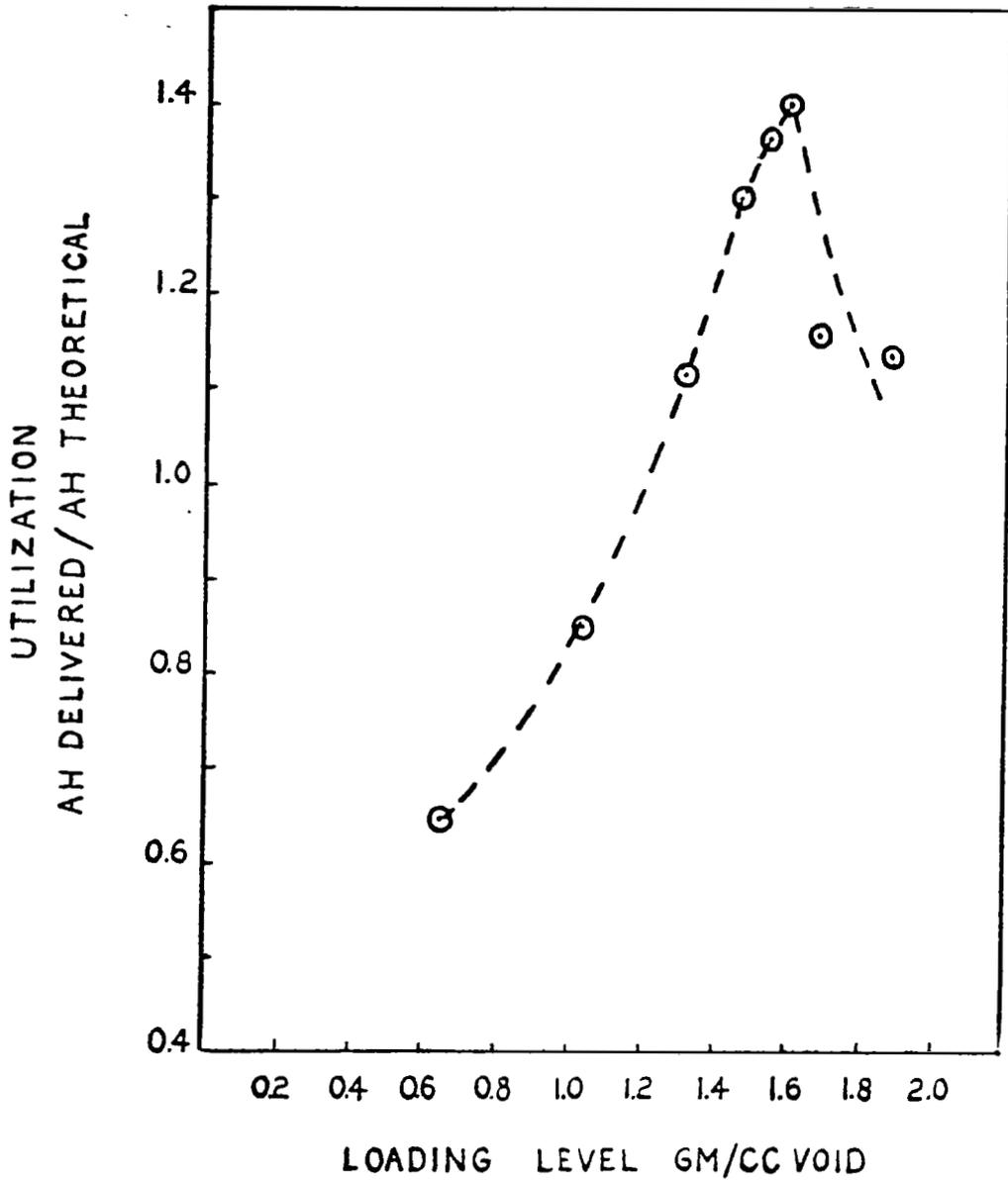
No. of Imp. Cycles	After Impregnation		After Forming		After Compression at 780 kg/cm <sup>2</sup>			
	Thick. cm	Wt. of Ni(OH) <sub>2</sub> g	Thick. cm	Wt. of Ni(OH) <sub>2</sub> g	Thick. cm	Wt. of Ni(OH) <sub>2</sub> g	Vol. of Ni(OH) <sub>2</sub> cm <sup>3</sup>	Density of Ni(OH) <sub>2</sub> g/cm <sup>3</sup>
1	0.0749	0.2124	0.0726	0.2213	0.0323	0.2213	0.279	0.79
2	0.0757	0.4032	0.0742	0.4112	0.0340	0.4112	0.303	1.36
3	0.0787	0.6439	0.0805	0.6659	0.0422	0.6659	0.412	1.62
4	0.0790	0.8225	0.0861	0.8421	0.0495	0.8421	0.536	1.59
5	0.0798	1.0198	0.0869	0.9283	0.0528	0.9283	0.580	1.60
6	0.0792	1.1665	0.0940	1.0835	0.0587	1.0835	0.652	1.66
7	0.0818	1.2147	0.0861	0.9878	0.0554	0.9878	0.618	1.60
8	0.0833	1.3923	0.0805	0.7597	0.0577	0.7587	0.653	1.16
9	0.0859	1.5523	0.0856	1.0132	0.0615	1.0132	0.699	1.45
10	0.0833	1.5856	0.0861	1.1053	0.0635	1.1053	0.733	1.51
11	0.0851	1.6793	0.0935	1.1097	0.0610	1.1097	0.694	1.60
12	0.0767	1.4766	0.0980	0.9163	0.0683	0.9163	0.816	1.12

Figure 5-64

TABLE III  
COMPRESSION OF CATHODIC IMPREGNATED ELECTRODES

Imp. Time Min.	After Impregnation		After Forming		After Compression at 780 kg/cm <sup>2</sup>			
	Thick. cm	Wt. of Ni(OH) <sub>2</sub> g	Thick. cm	Wt. of Ni(OH) <sub>2</sub> g	Thick. cm	Wt. of Ni(OH) <sub>2</sub> g	Vol. of Ni(OH) <sub>2</sub> cm <sup>3</sup>	Density of Ni(OH) <sub>2</sub> g/cm <sup>3</sup>
2	0.0732	0.3044	0.0729	0.3010	0.0356	0.3010	0.312	.97
4	0.0732	0.6109	0.0714	0.5959	0.0447	0.5959	0.429	1.39
6	0.0744	0.8531	0.0744	0.8259	0.0513	0.8259	0.536	1.64
8	0.0810	1.0817	0.0818	0.9930	0.0579	0.9930	0.623	1.59
10	0.0982	1.4190	0.0859	1.1004	0.0605	1.1004	0.664	1.66
12	0.1153	1.6295	0.0851	1.0827	0.0607	1.0827	0.669	1.62

Figure 5-65



V.J. PUGLISI GSFC WORKSHOP 1976

Figure 5-66

SESSION VI

NICKEL-HYDROGEN TECHNOLOGY

M. Tasevoli, Chairman  
Goddard Space Flight Center



## NICKEL ELECTRODE PLATE THICKENING STUDY

M. Bernhardt and D. Maurer  
Bell Laboratories

I would like to begin by saying that this paper will be given in two parts. The first part I will be presenting, and the second part will be given by Dean Maurer.

I would like to report on the interim results of a study on the rate of thickening of the nickel electrode.

One of the generally accepted failure modes of geosynchronous nickel-cadmium batteries is capacity loss, high resistance from shorts caused by excessive separator compression resulting from the thickness growth of the nickel electrode with cycling.

Until recently, little or no information existed on the effect of various operational parameters on the rate of this process. This multivariate study of individual electrodes was undertaken to determine some of these effects under geosynchronous type of conditions in support of the AT&T/GT&E satellite programs with COMSTAR and follow-on systems. To date, 36 combinations have been measured long enough to see trends.

This paper describes preliminary results on temperature, electrolyte composition, manufacturing lot, cycle parameters, and reconditioning methods. Let me tell you a little bit about the experimental procedure.

The plates were cut to 1.5 by 1.5 inches and cycled with large cadmium counter electrodes in specially designed lucite flooded cell containers to prevent fringe field effects.

The holders were filled with the appropriate electrolyte to a level slightly above the electrodes. A thin layer of high-purity mineral oil was floated on the surface of the solution to retard evaporation and the formation of carbonate. The cells were cycled in series and received constant current charge and discharge.

Individual diode protection networks were used for low voltage cut out to bypass the discharge current when cell voltage reached approximately 0.6 of a volt.

(Figure 6-1)

Table I is an outline and description of each of the variables investigated. The variables will be temperature, manufacturing lot, electrolyte composition, and test regime.

The first three temperatures we used were zero, room temperature, and 45°C. The cells that were at room temperature were exposed to controlled room temperature which was 23°C, plus or minus two degrees.

The ones at 0°C and 45°C were cycled in temperature cabinets that were maintained at approximately plus or minus one degree Centigrade.

The electrodes used in this study were BTL electrochemically deposited plates and General Electric chemically deposited plates. The BTL electrodes were made from the same sinter lot using nickel screen substrate and impregnated in-house. They were approximately 20 mils thick. The General Electric electrodes were all of the type used in COMSTAR, which was the PQ type and contained perforated sheet substrates which was nickel plated iron. They were approximately 27 mils thick.

Lots 9 and 12 were taken from COMSTAR, and lot 9 and lot 12 cells had gone through qualification testing. Lot 19 positives were approved electrode samples from a recent build of COMSTAR cells but had not actually been assembled into the cells.

All the GE plates were made by the CD process. There were five electrolyte compositions tested. You see the 30 percent KOH and 20 percent KOH used because they typify the range of concentration which may be found in sealed cells.

CO<sub>3</sub> was actually a solution of 3.5-molar potassium hydroxide and 1.8-molar potassium carbonate. This was included to simulate the effect of nylon degradation products from the separator.

K/Na was a solution of 50 percent 7-molar potassium hydroxide and 50-percent sodium hydroxide. It has been a consideration to add sodium to the electrolyte to improve charge efficiency at high temperature, and we examined its effect on rate of thickening.

An additional electrolyte not included in this summary was a solution of nylon which we hydrolyzed at 200°F and 30 percent KOH. The cell gave no capacity when cycled, and unfortunately there was insufficient data to include this in the population.

The last variable was test regime. Tests 1A and 1B were at C/6 charge rate. Test 2A was C/20 charge rate all for 110 percent returned; test 3A was a dual charge consisting of C/6 for 3 hours, 58 minutes. This was also 110 percent charge returns followed by C/30 trickle charge for 6 hours, 50 minutes. The latter is more typical of cycles seen in geosynchronous orbit.

All tests received standard C/2 discharges to 60-percent depth. The cells were continuously cycled according to their test regime for 12 days, which was about 50 cycles, to simulate an eclipse season.

After each eclipse season, all groups were fully discharged and given a reconditioning cycle. The 1A, 2A, and 3A groups received a C/40 discharge to 0.6 of a volt.

Group 1B differed only in its reconditioning cycle which involved repetitive discharge at C/40 for 8 hours, followed by 16 hours of open circuit until it reached again 0.6 of a volt. This is so the cell does not see more than 8 hours of discharge in a 24-hour period.

Following reconditioning, the oil was floated off the surface of the electrolyte, and the electrodes were removed for thickness measurements and visual inspection.

Wet-plate measurements were made in five places with a hand-held micrometer accurate to plus or minus a tenth of a mil. Visual deterioration such as blisters, cracking, flaking was all noted. If the deterioration was advanced, the electrode was replaced. Fresh electrolyte and oil were added after each eclipse season.

The mean thickness for each individual electrode was used to calculate a percentage thickness increase and a typical result is shown in Figure 6-2.

(Figure 6-2)

Percent thickness and cycle number.

A linear regression was done on each set of data points, and at least three eclipse seasons were accumulated in all cases. The slope of the regression line was used for a comparison and analysis discussed next. No attempt has been made at this time to calculate the statistical significance of these comparisons; however, an analysis will be made at the completion of the experimental program and reported later.

Now, as we expected, the BTL electrochemically impregnated electrodes demonstrated overall superiority in all testing conditions and showed no growth within the experimental error up to about 800 cycles. We have gone that far so far.

(Figure 6-3)

This figure shows a comparison with two GE chemically impregnated lots under similar test conditions. The scale on the last one we saw goes below zero, so if you can follow the zero line, that's where the BTL electrode, the slope was almost at zero. The two top lines are the GE plates.

What we generally use to qualify our electrochemically deposit on plates is an accelerated test. I won't go into the description, but Dean is going to give this brief description with some typical results. He will show you that in a few minutes.

(Figure 6-4)

The most surprising results of this study can be seen in this figure, in which, for each electrolyte, the average slope of all other conditions is plotted versus the temperature. The temperature, as you see here, is not monotonic. The growth rate is lowest near room temperature. It gets larger at both higher and lower temperatures.

A more detailed analysis of this effect will be carried out in a later paper. There are probably two mechanisms involved:

Expansion due to forces resulting from density changes between charge and discharge at higher temperature and forces resulting from fluid gas flow in the capillary structure which are controlled by viscosity effects at lower temperature. This effect is probably also responsible for the effect of concentrations of KOH, although the possibility of structure effects cannot be ruled out.

The high rate for carbonate at 45°C is undoubtedly due to corrosion effects. The high rate for the K/Na mixture, the potassium sodium, is probably due to the cation exchange which becomes significant at elevated temperatures with the smaller sodium ions. This is in line with the observed capacity degradation at room temperature, in the electrolyte containing one normal lithium hydroxide. The study has been done.

Another significant result is shown in Figure 6-5.

(Figure 6-5)

Here, we have the average slope for each lot number plotted against the temperature. You can see the lot-to-lot variability is as large as most of the other variables, and clearly indicates the need for an accelerated test and requirements for lot acceptance prior to cell assembly for flight programs still forced to use chemically impregnated plates.

This is especially true for programs requiring faster cycling where plate thickening is more likely to limit life before separator degradation. Clearly electrochemically impregnated plates are the best approach. However, if the process is not properly controlled, extensive growth can still occur as Dean will show with the accelerated test studies.

The effect of the cycle regime has not been studied as extensively as the other variables; however, the effects can be seen by calculating the average ratio of the slopes for relevant sets of conditions.

(Figure 6-6)

Table II shows this ratio at 23°C for the effect of reconditioning methods, 1B and 1A, and the effect of trickle charge, 3A and 1A.

As can be seen, the interrupted reconditioning results in more than 50 percent greater growth than the standard method. No explanation is offered at this time.

The trickle charge period following the standard charge in 3A is seen to result in three times the thickening rate than without it. This probably is due to the same fluid gas flow forces which give rise to the generally higher rates at low temperature. This effect merits further study but indicates that the trickle charge should be minimized, but probably not eliminated due to the danger of cadmium migration.

The problem can be eliminated, of course, on new designs with the electrochemical impregnation.

In conclusion, this study of plate growth leads to the following conclusions insofar as the flooded electrode measurements can be extrapolated to the starved, sealed cell conditions.

A major thing would be BTL electrochemically impregnated electrodes exhibited no growth under any of the conditions tested.

The growth rate of chemically impregnated plates is increased at temperatures both higher and lower than room temperatures, suggesting that satellite battery temperature reduction to minimize separator degradation must be tempered by plate-growth rate considerations.

Lot-to-lot variability in the growth rate of chemically impregnated plates is larger than the effects of most of the other variables.

And last, the effect of trickle charge following the normal charge results in a large increase in thickening rates.

The trickle charge probably should not be eliminated on existing satellites, however, due to the danger of cadmium migration on open circuit. On the other hand, changes in all these problems can be eliminated by using properly prepared electrochemically impregnated electrodes.

MAURER: I was going to talk about an accelerated test method for electrochemical positives; however, after the nomenclature discussion this morning I won't talk about an accelerated test. I am going to talk about a fast test.

(Figure 6-7)

We have been using a test method in the lab for quite a number of years that involves 10C charge and discharge with 100-percent overcharge. 10C was selected simply because it was a convenient number to use, easy to multiply by 10, and we used 100-percent overcharge to get a lot of this rather stressing condition into the evaluation routine. Then we used this on electrochemical electrodes to look at the effects of a number of different variables.

Some of this data was presented by Beauchamp and myself at the 1971 Collector Conference, and I just want to show it here to remind you that it can be used to measure these effects. This is the effect of cobalt concentration on the cycle life plotting capacity versus cycle number for different levels of cobalt which were achieved by simply adding cobalt to the impregnation bath.

Without cobalt the capacity falls off very rapidly. As soon as you get some in, you get greatly improved capacity maintenance, and an additional effect is that the electrodes without cobalt warp and bend a great deal. And with a little bit of cobalt, they remain flat.

Now, we can compare this with something at a somewhat lower rate: the 2C rate.

(Figure 6-8)

Again, there are the same electrode lots showing the same results.

(Overlay)

If I lay these on top of one another, you see the comparison between high and low rate is very close. There is a slight difference here on the 13-percent cobalt line, but this one again would be somewhat in agreement with the results on the accelerated study that was reported this morning.

Charge rates don't have all that big an acceleration factor. But they do allow you to get the information in a hurry.

(Figure 6-9)

This is the same thing on cadmium additive to the nickel electrode. The effect is similar, but doesn't give as good a result as cobalt. I haven't got any data on the combination of cadmium and cobalt both in the electrode.

(Figure 6-10)

This is the effect of lithium in the electrolyte. This work was done by Beauchamp and was published previously at the lab. It shows the effect of capacity with cycle number again at this 10C rate on an electrode with five-percent cobalt and the 32 percent line is up here.

This is a log plot now rather than linear that you saw on previous ones.

So this line is more or less in agreement with the one you saw before, and you put a little bit of lithium in, and you get a big degradation in capacity maintenance.

So one should be careful about adding lithium for these aerospace cells. You tend to cycle them quite a lot.

(Figure 6-11)

Next, with the interest in electrochemical electrodes for their thickening properties, we started using this method to look at that effect. By the way, the setup for this study is more or less the same as what was just described for the chemical plates, except, to handle the very high rates we put them in flooded cells that had a great deal of excess electrolyte. But again, minimizing fringe fields.

We had enough electrolyte in them so that we didn't change the composition significantly for perhaps the longest watering period which would be like a holiday weekend. Then, we put plastic covers over them to minimize the KOH spray they could get. The leads are gold plated alligator clips that have the solder joint protected with shrink tubing to prevent corrosion from taking place.

The capacity, or rather the discharge, is limited by meter relays instead of diodes.

Doing this, then stopping every so often to measure thickness, and looking at electrodes from a variety of sources, you get this kind of data.

(Figure 6-12)

You see, there are really four classes of electrodes here: There is the one we know and love, which doesn't grow at all; some that have a slight growth; some have a sudden growth for a few cycles and then flatten out or nearly flatten out; then another set that have that same thing with some greater increase.

This is really the result of the impregnation process or the sinter not being quite right in each particular case. And Tom O'Sullivan in my group has done some work along this line and has been able to reproduce those effects deliberately.

(Figure 6-13)

This is some of that data.

Basically, the problem is that you have to limit the loading of the electrode to the number that McHenry was talking about, 1.6 grams per cc of void as an average over the plate.

However, you also have to be careful that the active material distribution is uniform. You might have 1.6 grams averaged through the thickness of the plate, but it might be all located near the center. That is near the substrate or it might be all located out near the surface.

If you have those conditions, then you get this kind of an effect. And if you have it simply too high, you get this continual growth kind of an effect. But, if you limit it to a well distributed 1.6, then you get no growth.

The other things you have to watch out for, of course, are big voids in the sinter. The sinter needs to be uniform for distribution.

Now, to compare these high-rate growth rates with what you get at more common conditions, see the following figure.

This is a plot of some of the data that Madeline has just shown from that same study. The upper line represents the high-rate cycling data, and the lower two points here represent data on the same plate, taken from a different place on the same plate, done at the geosynchronous rates that she was talking about. So you get the same kind of slope. The displacement is probably due to measurement errors in the initial thickness measurement.

So the technique can, in fact, be used to get information about the quality of plates. I make no claim that I can compare a 1000- or a 2000-cycle plate from this study, directly to a sealed cell.

In a sealed cell, under some other kind of capacity conditions, I might very well get a different cycle life.

But, what I am saying is that the relative merits of plates on this test are probably carried over into the sealed cell.

I would like to take this opportunity to say one other thing about how this might relate to real life predictions or life mechanisms on geosynchronous batteries and the effects of reconditioning and that sort of thing that we have been discussing.

My view of this, of the voltage profiles that you see from orbital data, is that it involves several classes of things going on in the cell.

(Figure 6-14)

Some of which are visible in the voltage data and some of which are not. If I just plot some quality function, it might be voltage versus time or season in the geosynchronous orbit, I get some band that has this general shape.

It might be a bit flatter with some reconditioning methods, and a bit steeper with others. It is, in general, somewhat reversible, although it has an irreversible component.

(Overlay)

The reversibility part of it is what you really recover by the reconditioning method. But what this doesn't show are the effects of anything else going on in the cell (for example, separator degradation, which will proceed to the point that either the negative is fully charged and the cell blows up, or the separator is gone and it shorts out). And that will be seen in the outside world as a very sudden collapse of cell quality.

So that is going to be a vertical line out here, somewhere.

Then things like plate thickness increase. It will squeeze the separator, and then you will begin to get some degradation.

(Overlay)

So that is going to be a vertical line, but one with a very high slope. Depending on the particular cell design, all of these curves can move back and forth with respect to one another. Certain kinds of cell designs that are made with plate lots that have high thickness increase rates, or certain other conditions might have sudden failure like this.

For others where this plate thickness doesn't become such a problem, such as shallow DOD and so forth, this might move out here somewhere.

And this other mechanism will be the end-of-life feature.

My point is that just looking at the voltage data from the satellites and seeing the lack of degradation, one should limit the euphoria from such a situation because there may be things going on that will suddenly become visible shortly after you have made the measurement.

#### DISCUSSION

HALPERT: You mentioned with the process you know and love you seem to get uniform impregnation. But you also mentioned the fact that you have to have a nice, uniform sinter.

Where, pray tell, do you get a plaque with a uniform sinter?

MAURER: I leave that as an exercise for the student.

# TABLE I

## SUMMARY OF TEST CONDITIONS

### TEMP.

1. 0°
2. RT (23°C)
3. 45°

### LOT

1. BTL - BTL ED PLATES
2. 9 - GE CD PLATES FROM COMSTAR LOT 9 CELLS
3. 12 - GE CD PLATES FROM COMSTAR LOT 12 CELLS
4. 19 - GE CD PLATES TO BE USED IN RECENT CELLS OF COMSTAR DESIGN

### ELECTROLYTE COMPOSITION

1. 30% - 7M KOH
  2. 20% - 4M KOH
  3. CO<sub>3</sub> - 3.5 M KOH / 1.8 M K<sub>2</sub>CO<sub>3</sub> (SIMULATES EFFECT OF NYLON DEGRADATION)
  4. K/Na - 50% 7M KOH / 50% 10M NaOH (Na TO IMPROVE CHARGE EFFICIENCY)
- (CONDITIONS FOUND IN SEALED CELLS)

### TEST REGIME

1. 1A - C/6 CHG, C/2 DISCH; RECONDITION C/40 CONTINUOUS TO 0.6V
  2. 1B - C/6 CHG, C/2 DISCH; RECONDITION C/40, 8 HRS ON/16 HRS OFF TO 0.6V
  3. 2A - C/20 CHG, C/2 DISCH;
  4. 3A - C/6 CHG/C/30 CHG, C/2 DISCH;
- } RECONDITION SAME AS 1A

Figure 6-1

POSITIVE PLATE GROWTH DATA

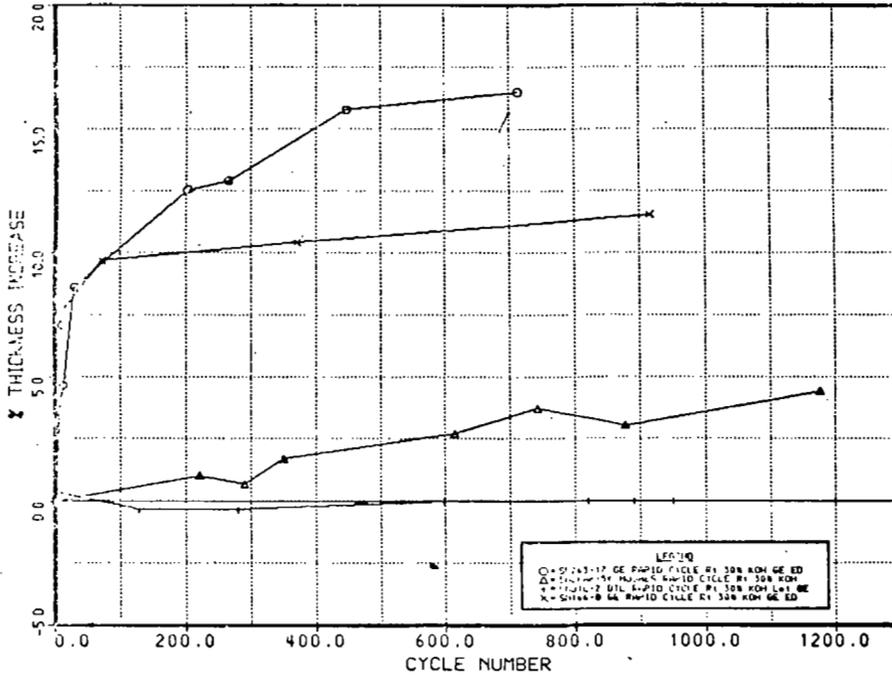


Figure 6-2

POSITIVE PLATE GROWTH DATA

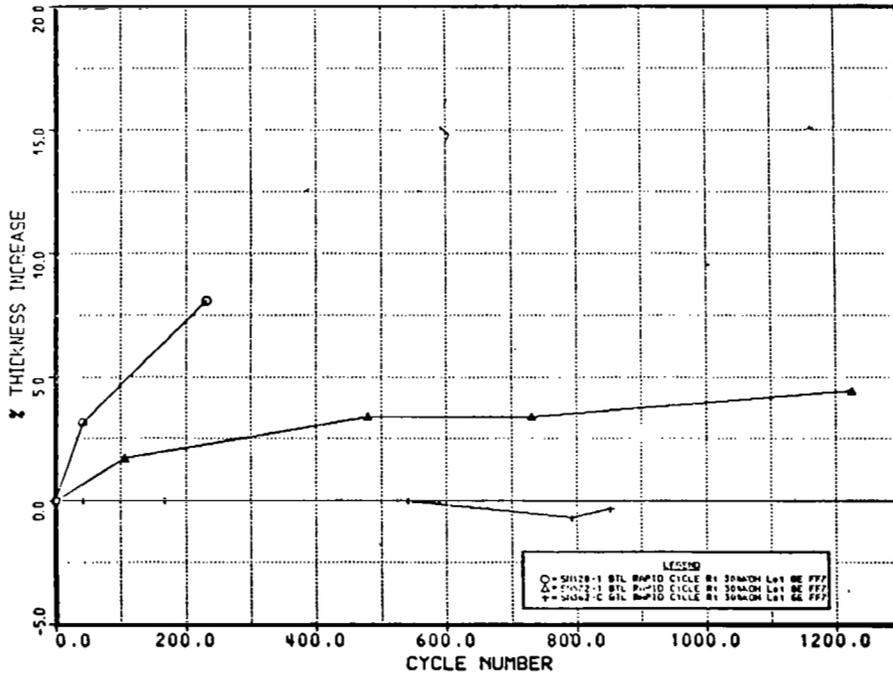


Figure 6-3

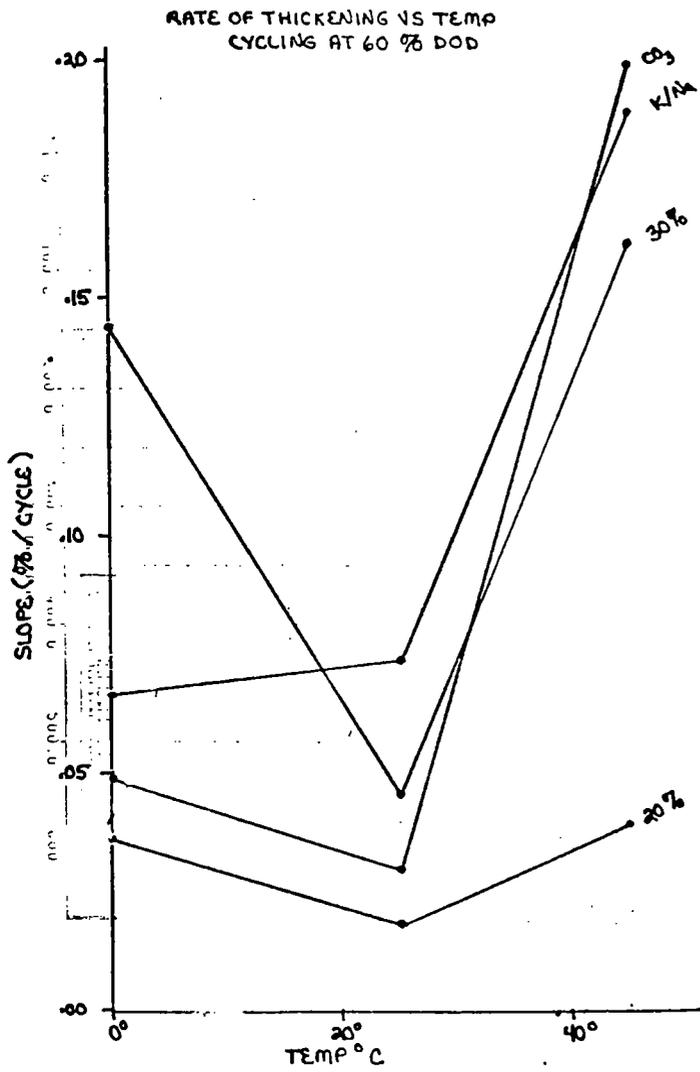


Figure 6-4

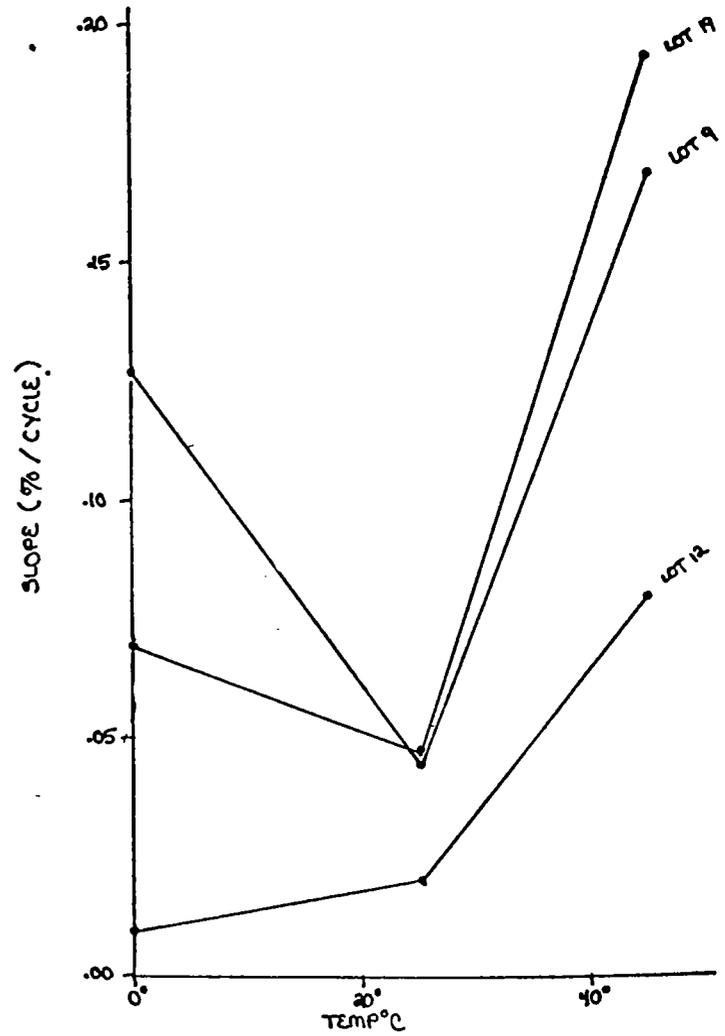


Figure 6-5

TABLE 2

Ratio of Thickening Rates at 23°C for Cycle Regime Pairs

<u>Regime Pair</u>	<u>Description</u>	<u>Ratio</u>
1B / 1A	Recondition 8Hrs on/16Hrs off Recondition Continuous	1.6
3A / 1A	C/6, 110%/C/30 Charge C/6, 110% Charge	3.0

Figure 6-6

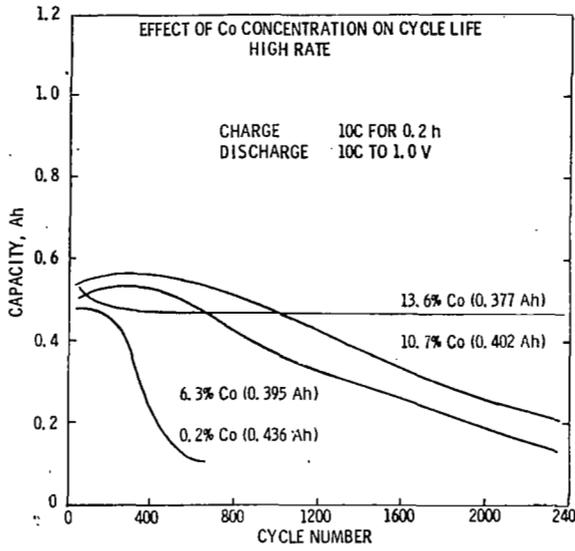


Figure 6-7

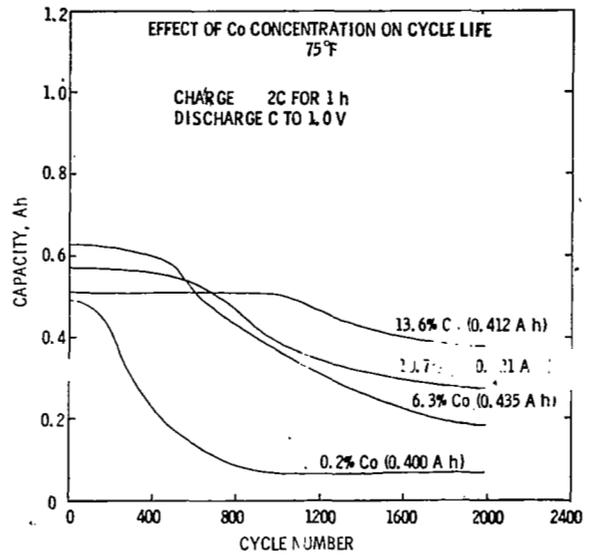


Figure 6-8

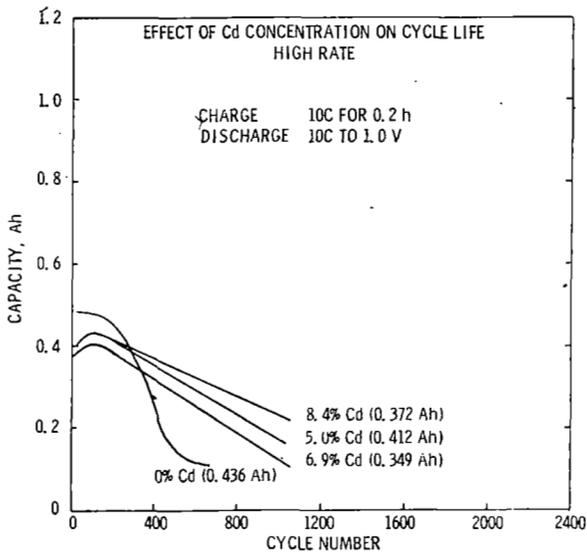


Figure 6-9

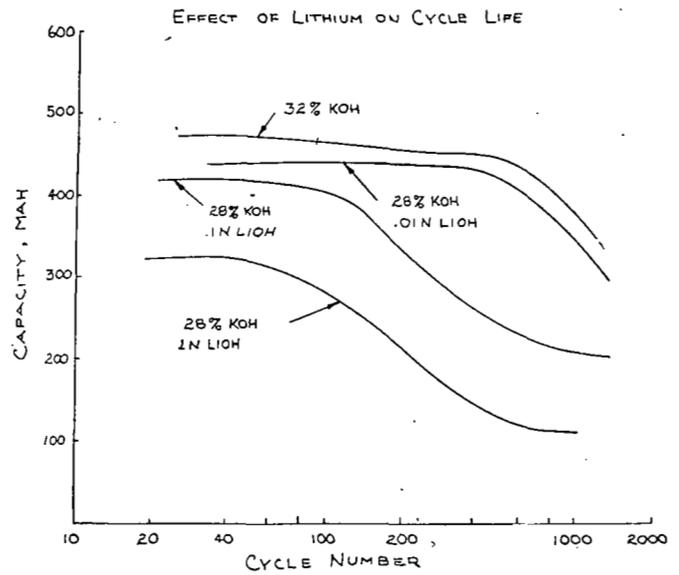


Figure 6-10

POSITIVE PLATE GROWTH DATA

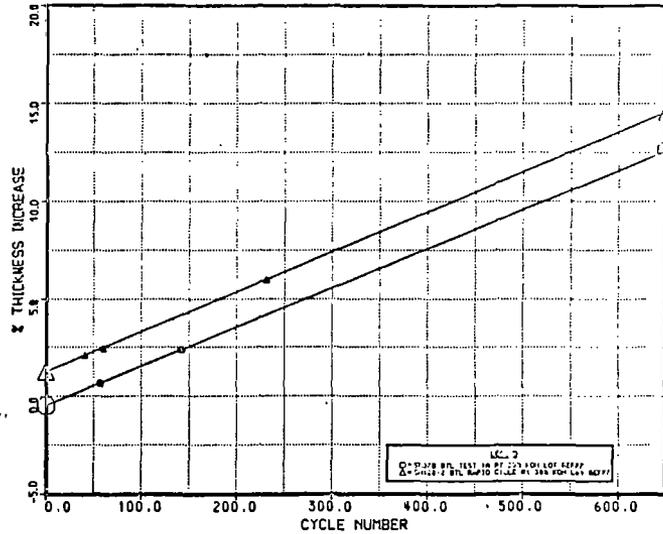


Figure 6-11

POSITIVE PLATE GROWTH DATA

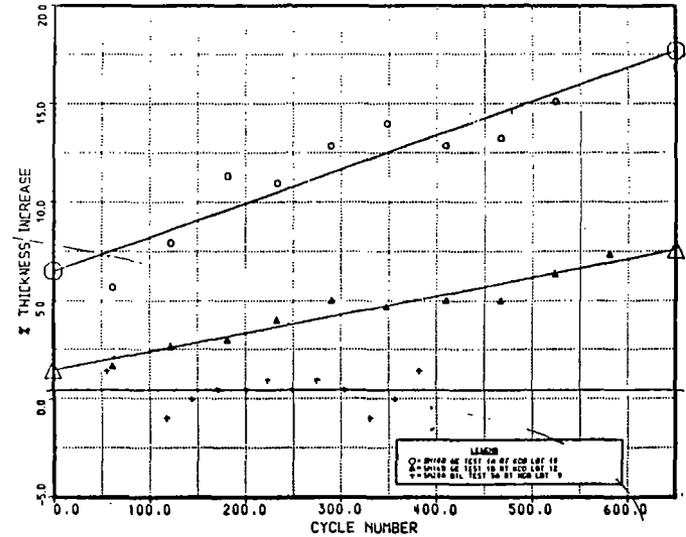


Figure 6-12

POSITIVE PLATE GROWTH DATA

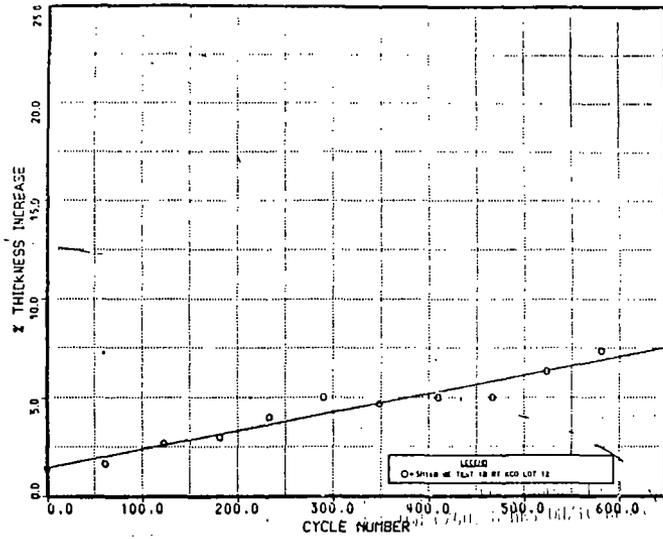


Figure 6-13

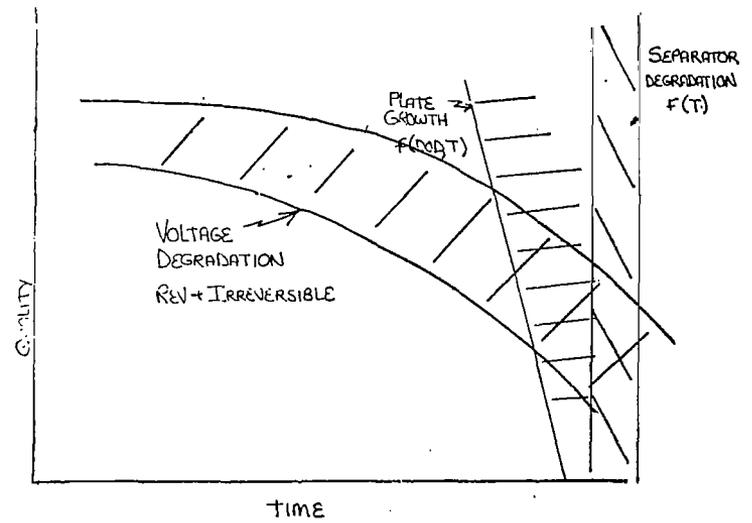


Figure 6-14



## AEROSPACE ELECTRODE LINE

L. Miller  
Eagle Picher

Let me just give you a little bit of history before I go directly into my paper.

For more than 20 years the Eagle Picher space-battery operations have been located in our Joplin, Missouri plant, and we have been procuring finished electrodes from our Colorado Springs facility. We consider this facility to be our commercial operation or high volume operation.

As of now, and at least starting about the last 6 months, we now have a new electrode facility in operation in our Joplin plant. We believe that this facility may be the first electrode-processing nickel cadmium and nickel hydrogen designed, developed, and dedicated solely to the production of electrodes for space-battery systems.

The facility offers production capacity for not only the chemical electrodes which we have been using for a great deal of time now, but also the newer electrochemical designs.

(Figures 6-15 and 6-16)

These are just a couple of vugraphs. I have a couple of more to give you an overview of the system. I might just comment on the production capability of the operation.

Right now, we are not really running at full capacity. We can produce about 150 square feet of plaque material in an eight-hour production shift. However, the design of the equipment is such that it is capable of handling three times this volume.

There are a number of unique design features that are specifically incorporated to produce a high-quality electrode. We have made these changes based upon our experience as part of the operation. Also, we are indebted to the recommendations and suggestions of Jerry Halpert and Floyd Ford.

Let me go through a couple of these items here.

1. A batch rather than a continuous operation mode was selected for better process control.
2. An independent equipment module design approach was taken to assure process solution isolation. In other words, electrode materials are themselves transferred from process tank to process tank, rather than the much easier and lower cost method of pumping in different process solutions into the same tank.

The benefits achieved here are elimination of the slow, but inevitable buildup of tank, plumbing, and solution reservoir contamination associated with partial solution mixing.

3. All equipment, even including the exhaust duct work, is constructed of stainless steel and all current carrying components such as buss bar and electrode process racks are constructed of pure nickel to prevent contamination.

4. Equipment design was easy and was designed for easy access to facilitate both internal and external cleaning.

5. Continuous in-line process monitoring and an analytical chemical laboratory dedicated to this operation assures achievement of the desired high degree of process control.

(Figures 6-17 and 6-18)

6. Each piece of 12 X 12 electrode material blank, and there is three per process rack, is connected to the process rack by four redundant, fusion welded nickel tab connections to ensure uniform current distribution within the parallel rack assembly.

7. In addition, each rack assembly offers an adjustable connection to the process tank buss bar, allowing fine tuning of current flow to achieve uniform current distribution through each parallel rack assembly.

8. During actual operation, process tank to reservoir solution recirculation provisions permitted the introduction of filtration and sedimentation steps to maintain ultra high solution purity levels.

9. The very important, final electrode material formation step, a unique high-voltage system was devised featuring multiple, series-connected small formation cells, again assuring uniform current distribution.

That's what you could see on your right over there if it were a better vugraph.

10. Each of the above formation cells is fixtured so as to permit frequent replacement of the electrolyte solution which, of course, always is heavily contaminated in this operation.

11. A special multistep cascade, deionized water washing technique followed by a vacuum drying step, produces finished electrode materials exhibiting the desired physical stability and cleanliness characteristics.

12. A series step deionizing system which means we have two deionizers connected in series so we have pretreatment as well as final treatment to ensure a very high quality deionized water source for all operations of the system.

In addition to the formation there, we have what we call our final electrode carbonate treatment equipment. Basically, there are two systems in operation depending on the customer's preference.

One involves a multiflushing of the finished welded cell, and the other involves a hot caustic dip – it can be boiling caustic – just prior to final cell assembly for carbonate reduction purposes.

With respect to the results, as I say, we have only been in operation for six months. We don't have long-term data, but some of the initial observations based upon our previous source of electrodes – we used to only use about one-half of the electrodes that we procured. The attrition was either as a result of out-of-weight range plaques, or physical defects associated with the electrode materials. We now use more than 90 percent of the electrodes produced.

One thing that was somewhat of a surprise to us is that generally when we built some fresh cells, we needed, through a series of burn-in cycles, to develop their capacity, or at least stabilize their capacity.

We find now that cells built with electrodes on this new line exhibit a long-term capacity from the very first cycle.

One of our observations is that the activity in the electrode appears to have been improved to the point that we can operate a cell design to 15 to 20 percent more electrolyte and still measure lower internal pressures on cycling.

#### DISCUSSION

FORD: Lee, I don't remember you commenting on making the plaques themselves. Are you making those in Joplin?

MILLER: At this time the raw sinter is still made in our Colorado Springs facility. There are plans to set up a new operation at Joplin for that, also.

FORD: Will you be automated with that, or are you going to use the old magnet technique?

MILLER: It is rather a tough decision right now. The dry sinter or the individual sintering process has certain advantages; the continuous or automated slurry has its own advantages. I would say right now the preference would be to probably go to the continuous slurry process.

GROSS: Lee, you indicated that it was determined that the batched process would be better than the continuous process.

Offhand, I would have guessed the other way around. Can you explain that a little bit further, please?

MILLER: Well, the batch process just lets you step into the middle of the process and make measurements more easily than a continuous process because it will be better control.

GROSS: The other point was, I have always felt that the electrochemical impregnation method had the potential to be a completely closed system, to be closed off from the atmosphere, and solved once and for all the problem of carbonates getting on the plates.

Apparently, you elected not to do that, or couldn't, and I wondered if you would explain why that happened.

MILLER: I am not sure what you mean by that, Sid. There is a great deal of gas evolution associated with the electrochemical process, more so than the chemical process.

GROSS: Yes, evolution. Would that mean gas would go out and you could have gas evolve without allowing atmospheric gases to get in?

MILLER: Maybe I don't understand your question. What do you mean by a closed system?

GROSS: Closed from the atmosphere, from the contamination of carbon dioxide and gas, which produces carbonates on the plates during manufacture.

MILLER: One thing you can do with the electrochemical process though is to finish the impregnation step in the acid state, so you don't have to be as careful as in the chemical process with respect to storage of plaques between operations.



Figure 6-15



Figure 6-16

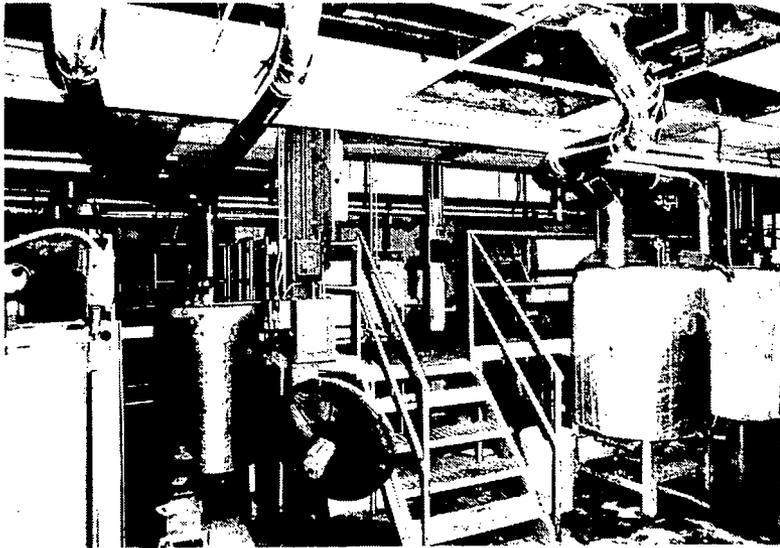


Figure 6-17

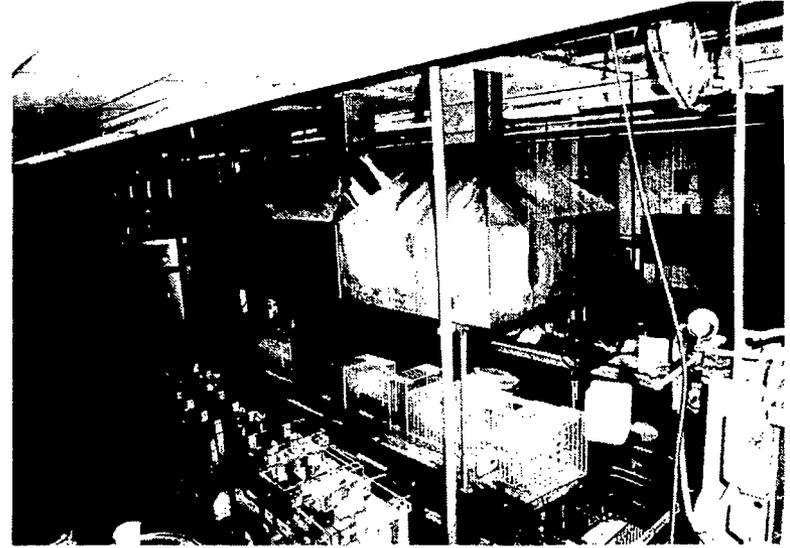


Figure 6-18



## UPDATE, COMPARING DIFFERENT PLATE TREATMENTS AND DESIGN

D. Baer  
NASA/GSFC

I will try to keep this as brief as possible. This is an update of a paper I presented last year comparing different plate treatments and designs. For those who weren't here last year, and to refresh everybody's memory, including my own, I will first discuss the different designs, briefly.

(Figure 6-19)

The group 1 cells were the control, and they represent present aerospace practices and processes with no extra treatments, nonwoven nylon separator. They are PQ treated positives, then they went through decarbonation process, and they had the IUE loading metals, 31 percent KOH.

The group 2 had teflon treatment, and they were the same as the controls, except they had the teflon treatment.

Group 3 were the same as the controls, except they had a silver treatment.

Group 4 were a lightly loaded plate, and they were from a different spiral than the control.

Group 5 was also from a different spiral, and they did not receive the PQ treatment.

Group 6 was also identical to the control, except it had polypropylene separator.

Group 7 was the old plate design that they used during the '60s, and they also used the old ECT process and there was no depower.

Group 8 was an AK plate also, except that it used the present aerospace processes.

Also listed are the typical thicknesses for positive, negatives.

The loading levels, the final KOH quantity and the precharge adjustment.

To date, we have seen them under test at Crane and they have completed six months of tests. We ran a capacity check after 2900 cycles.

(Figure 6-20)

The way these cells are cycled, it was a 90-minute orbit at 20°C, 40-percent DOD, and we had a voltage-limit charge control. We tried to maintain a certain return at about 115 percent. The discharge rate during this test, and also during the cycling was 9.6 amperes.

Just for comparison, there are some capacities, some precycling capacities. Unfortunately, it wasn't until the first cell came down to 27 volts, so not all the cells were discharged down. So we don't have an accurate comparison, although it does give you a feel for what the capacity of each cell is. During capacity check, we only discharged the one cell.

As you can see, the solid line is your controls, and you can see all of them pretty well follow the same profile, although it does look like the polypropylene had a little more capacity fade than the other cell groups.

Possibly the lightly loaded one had a little more fading, too. I would expect them to have a little less capacity to begin with, so it is rather hard to tell.

(Figure 6-21)

Now, the other half of the test is a little more revealing. These are all tested the same.

This is the old plate, and you can see it has very little capacity loss. In fact, there is a little bit of gain. The X's are not PQ treating. That had very little capacity fading also. And the voltage was higher on all three of them.

It had a higher discharge profile, but it did seem to have a lot of capacity fade. It is the old plate with the new process.

I am not sure why that is, but we did have quite a bit of trouble with that pack. We had voltage divergence, and we couldn't maintain a percent return, so we had to remove two of the cells. So that pack had a problem.

Granted, we cannot draw too many conclusions from a discharge of one cell from each group in just the one capacity check, but it sure looks like the plates without the cadmium treatment in the positives have a higher discharge profile, and there is some evidence here that indicates you aren't getting as much capacity fading either. These are GE 12-ampere hour cells, by the way.

## DISCUSSION

DUNLOP: Is there teflon treatment in that last group?

BAER: No, teflon treatment was in the first group, and it pretty well followed the control profile.

It is rather hard to tell whether there is any capacity fading between the control and the teflon and the silver treatments. They all seem to be in the same area as far as the capacity goes and voltages pretty well fell on top of each other.

DUNLOP: The temperature was what?

BAER: 20°C.

## CELL DESIGN VARIABLES - GE 12 AH CELL

VARIABLE	GROUP #	TYPICAL POSITIVE THICKNESS cm	TYPICAL NEGATIVE THICKNESS cm	POSITIVE LOADING gm/dm <sup>3</sup> OF SINTER	NEGATIVE LOADING gm/dm <sup>3</sup> OF SINTER	FINAL KOH QUANTITY cc N/V3 <sup>rd</sup> **	PRECHARGE ADJUST*** Ah
CONTROL*	1	0.069	0.079	2095	2180	40/40	4.6
TEFLON TREATMENT	2	0.069	0.079	2095	2180	48/49	4.6
SILVER TREATMENT	3	0.069	0.079	2095	2180	43/44	4.6
LIGHT LOADING	4	0.069	0.079	1840	1833	45/46	4.6
NO P.Q. TREATMENT	5	0.069	0.079	2113	2180	40.3/41.5	4.6
POLYPROPYLENE SEPARATOR	6	0.069	0.079	2095	2180	39/40	4.6
A.K. PLATE-1968 DESIGN, NO PQ OLD ECT PROCESS, NO DECARB PROCESS	7	0.081 (UNSIZE)	0.066	2130	2542	38/39	0
A.K. PLATE-1968 DESIGN, NO PQ PRESENT AEROSPACE CELL PROCESSES	8	0.081 (UNSIZE)	0.066	2130	2542	39/40	1.8

\*CONTROL CELL REPRESENTS PRESENT AEROSPACE DESIGN AND PROCESSES WITH NO EXTRA TREATMENTS: NONWOVEN NYLON SEPARATOR, P.Q. TREATED POSITIVES, DECARBONATION PROCESS, IUE LOADING LEVELS, 31% KOH.

\*\*TWO CELLS IN EACH GROUP CONTAINED SIGNAL ELECTRODES.

\*\*\*BASED ON 228 cc O<sup>2</sup>/Ah.

Figure 6-19

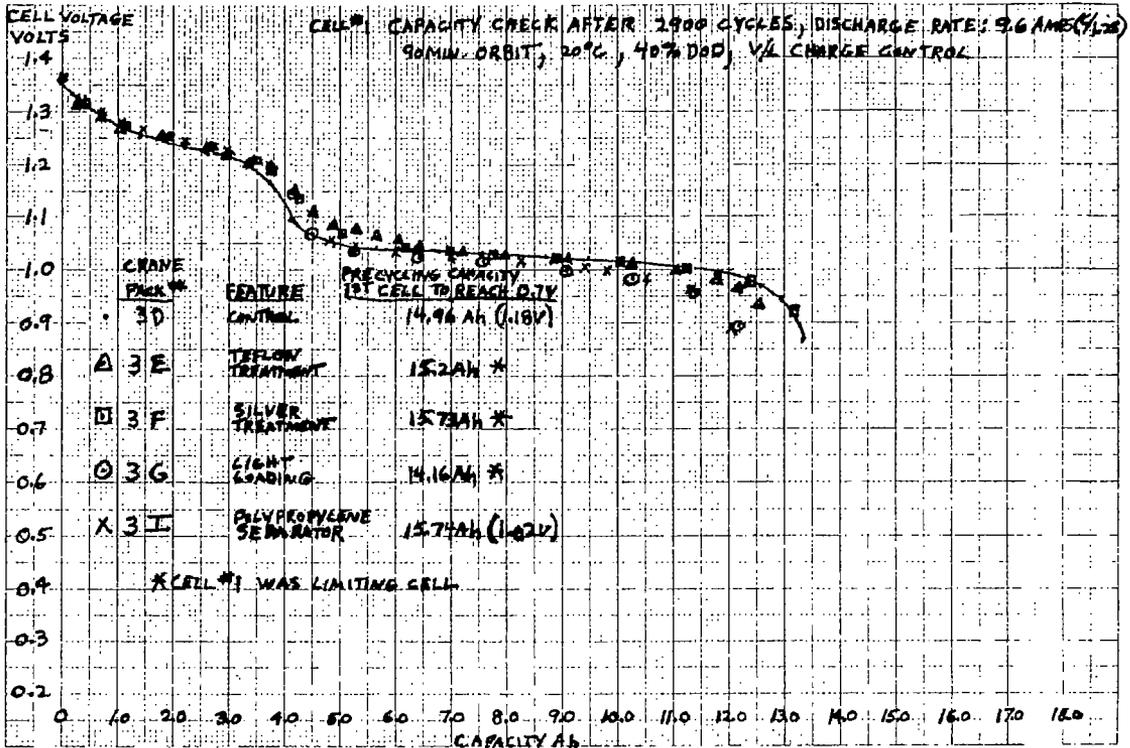


Figure 6-20

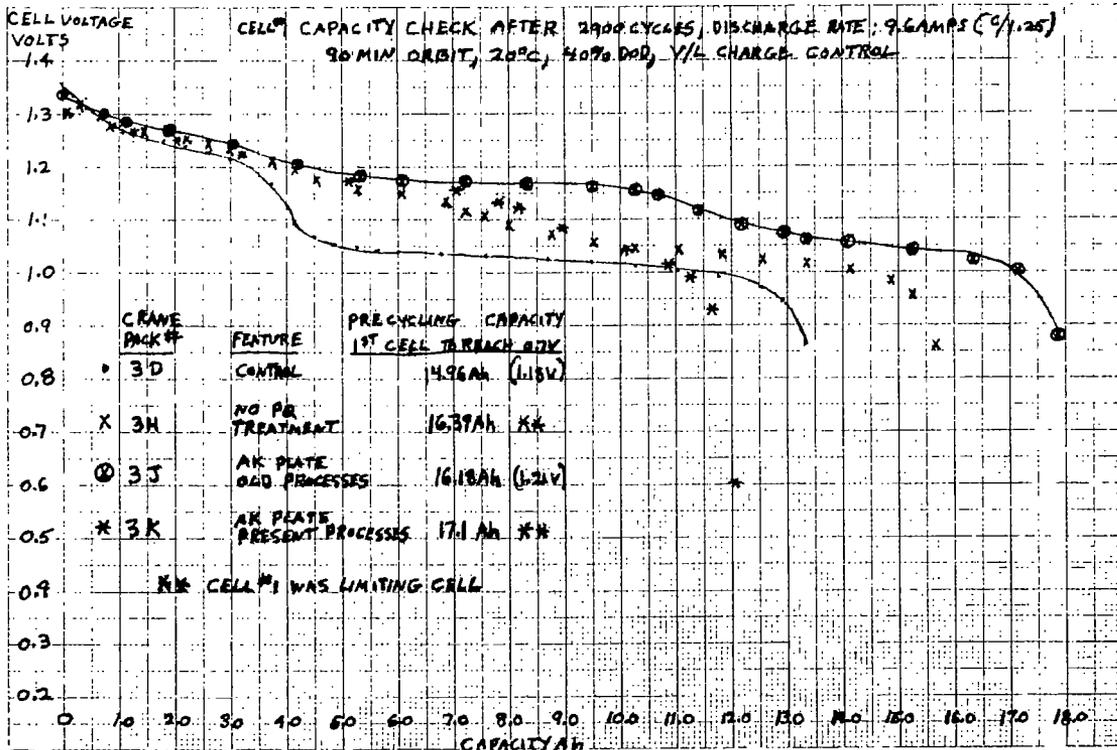


Figure 6-21



## INTELSAT-V: NICKEL-HYDROGEN BATTERY

G. Van Ommering  
Ford

I would like to talk a little bit about the nickel-hydrogen program we are doing for Intelsat V. I guess I said a few words about that on Tuesday, but I will just go through this thing as planned.

First, I will give you a little bit of background on the program.

We will have the first slide, and then immediately after that, the second slide.

(Figure 6-22)

The program we are doing for Intelsat is divided into three basic parts: Phase I is the design study that was completed in about February 1979, and that primarily involved doing some basic studies as to what was involved in incorporating the nickel-hydrogen battery into a spacecraft which was originally designed to incorporate a nickel-cadmium battery.

Some additions and minor changes to the spacecraft were required and were resolved in that period. Also, the basic design of the battery was defined at that time.

Right now we are going through a development phase, that is our Phase II. We are making pretty good progress in that.

Under that phase we are procuring battery cells. We started out with two vendors, and eventually selected Eagle Picher as our battery cell vendor. We have been testing these battery cells, and we built an engineering model battery that we just completed about a week and a half ago which is currently in test.

The remainder of Phase II will involve the fabrication of five more batteries, two for qualification purposes and three for integration purposes. In addition, the engineering model battery will be refurbished to serve as integration battery.

We also are doing battery life testing. We have started the life test on the engineering model cells. That is currently going on. We will also be doing life test on the qualification batteries, and COMSAT laboratories will be doing life testing on one of the control batteries.

On the basis of the results of this Phase II, and in particular the cycling results, we expect that Intelsat will award Phase III, probably in March 1980, which is currently an Intelsat option and which will involve the fabrication of batteries for the Intelsat F5 through F7 spacecraft. There has been a recent addition of the possibility of pressure that will circumvent spacecraft for which nickel hydrogen will also be used. That's the basic structure of the program.

(Figure 6-23)

In this next slide, I would like to briefly revisit some of the reasons why we think, at this point, nickel hydrogen is a good technology to develop into actual spacecraft application and use.

I will just highlight a few of these items. The negative electrode, obviously, is a bit less of a problem than the cadmium electrode NiCads. We had no cadmium migration; no recrystallization problems. The electrode is purely catalytic and because of that does not significantly change over thousands of cycles. It is something we simply do not have to worry about very much.

The separator does not degrade with time as nylon does. Asbestos is much more stable and also is much more wettable in the long run than nylon is, particularly in competition with nickel electrode.

We have a bit more electrolyte in these cells per ampere-hour than we have in typical NiCad cells which also have several benefits as listed on the slide.

Another significant benefit is state-of-charge indication that we get by simple pressure measurement, which will permit us to minimize overcharge. Conceivably this might eventually get developed into automatic charge maintenance of nickel-hydrogen batteries.

Lastly, we are introducing the electrochemically impregnated nickel electrode into actual spacecraft use through this nickel-hydrogen battery. There is a lot of experience on that; several papers have been presented in the past at this workshop.

We expect, in addition to all these advantages, nickel hydrogen will add a 10-year life on the synchronous spacecraft, and possibly longer. And that is our main reason for this strong interest in applying it at this point.

The weight advantage, which was a bit over sold early in the nickel-hydrogen development, isn't really that significant. We are saving weight on the design of our battery, as I will show you, but it is nothing to write home about. It is not spectacular. We can use that weight, it is great, but it is not our main reason for doing this.

(Figure 6-24)

On our next slide I would just like to complete this nickel hydrogen versus nickel cadmium background picture a bit. I would like to show some data taken at Ford on the nickel-hydrogen battery that we have on loan from Intelsat.

This is a prototype NTS-2 battery. We are cycling that right alongside Intelsat-V nickel-cadmium battery. They have essentially the same actual capacity, 38-ampere hours approximately, and we are cycling them under the exact same regime. And typically this is the kind of performance that we get through an eclipse season showing the end-of-discharge voltage there as a function of eclipse data.

You can see we are getting about 20 millivolts, maybe 30 millivolts, better performance with nickel hydrogen, which was expected simply on the basis of the equilibrium voltage at the couple. We are getting that consistently. Essentially, the nickel-hydrogen battery, I guess, is about three years old; stored in all sorts of ways, generally at room temperature. It has not really been treated particularly friendly. It is holding up quite well.

Now we will get into the real Intelsat-V battery in the next slides.

(Figure 6-25)

I have shown the general characteristics that are more appropriate with the ground rules we are working under for this nickel-hydrogen battery.

The major ground rules are that we should have complete spacecraft interchangeability between nickel hydrogen and nickel cadmium. The way the implementation of nickel hydrogen will be handled is that the decision between building or using the nickel cadmium or the nickel hydrogen in say, the F5 spacecraft, will be made rather late – very shortly before the launch of the spacecraft – and we are actually building the NiCad batteries right alongside the nickel-hydrogen batteries for the spacecraft just to give us maximum insurance because it is a program that involves a bit of technical risk.

The spacecraft impact has to be minimal. All the things that plug into the battery have to be identical. We have achieved that without any great difficulty.

The second item there shows that we have two 27-cell assemblies as opposed to the 28-cell assemblies that we had for nickel cadmium. The reason for that is that we have a slightly higher charge rate also for nickel hydrogen. We simply eliminated one cell to make sure the charging system could handle the battery.

That had the advantage of making available an additional telemetry channel which we are using to transmit a strain-gauge signal from one of the cells so that we will have some information as to what the pressure, and consequently the state of charge is at the battery.

We are using Intelsat cell design which has been proven on NTS-2 and was very successful, and is still very successful there.

There are a few very, very minor changes which were considered to be improvements, but they do not affect the basic design of the cell.

Intelsat gave us a maximum DOD guideline of 70 percent based on a lot of cycling data that existed. We are actually using more in the range of 58 to 65 percent, so we have a little margin there.

We control the temperature so that it does not go below 0°C, heaters automatically switch on at 1°C, and switch off slightly higher than that.

We have the same wide range of charge currents that John Armantrout discussed yesterday for the nickel-cadmium battery, and we have reconditioning capability since it is built into the spacecraft. We may or may not need that.

(Figure 6-26)

On this slide there are a few more characteristics. I am not sure I am going to develop them.

The spacecraft mode is slightly higher than is shown here, 930 watts, now, 465 per battery constant power. The current load uses about 61-percent DOD in the worst-case voltage situation. Normal beginning-of-life expectation is about 58 percent. Actually through all these various conditions, it runs about 10 percent higher than nickel-cadmium battery, generally.

Let's see, what else is worth highlighting here. The heat dissipation is somewhat different from the nickel-cadmium battery. We have slightly higher dissipation on discharge, but then during charge we have more endothermic period than the NiCad has. And during most of the charge the nickel hydrogen puts out a bit less heat than the NiCad.

The total heat dissipation over a full cycle is expected to be equal to or possibly slightly less than the nickel cadmium shows. With the increased heat capacity, which we have due to the added electrolyte, the actual range of temperatures that are predicted for the nickel-hydrogen battery is about the same as for the NiCad. We are looking at approximately predicted actual values of 1°C to 23°C.

(Figure 6-27)

This slide summarizes the telemetry we have on the battery. Twenty-seven battery cell voltages are available. Battery pressure is on the 28th voltage channel. We have thermistors on the battery to permit measurement of the temperature and compensation of the strain gauge signal, because we need to compensate for the effect of temperature on the pressure of the battery.

(Figure 6-28)

This slide shows the basic layout we are dealing with on the spacecraft panel. The array of little circles is the outline of the nickel-hydrogen battery that really is a nice, tight fit.

The dotted line superimposed on the nickel-hydrogen battery indicates the location of the nickel-cadmium battery.

As it looks here, the nickel-hydrogen battery isn't really that much larger than the nickel-cadmium battery. Probably a bit misleading because some of the lines on the outside of the nickel-cadmium profile are really a little thermal shield which we really don't consider part of the battery.

But you can see that we really didn't have to move much equipment to put that battery in. There is one little box in the south panel that was moved over a little bit, and that was really all that was necessary.

The battery was also higher than the nickel-cadmium battery. There was sufficient clearance to handle that, so mechanically there was really no difficulty in getting that battery on the spacecraft.

(Figure 6-29)

If this conference would have been a week later, I would have had a photograph here, but this is basically what that nickel-hydrogen battery looks like.

I will just highlight a few of the features. Electrically, we are trying to keep the thing fairly clean by running all the sense wires through the bottom of the battery. It is a fairly clean package when it is together. There are a lot of wires there, but it goes together fairly easily.

We have, of course, redundant power wire, also a diode bypass potential, and that is mounted right inside the little aluminum sleeves that contain each of the cells. That makes for a reasonably compact structure. The top surface of the cells are insulated with polyurethane to prevent any accidental grounding.

There was a little episode with NTS-2 that we would rather forget.

Mechanically, the cells are held in aluminum sleeves which fit fairly tightly around them. There is a thin layer, approximately 15 mils of silicon rubber between and that serves to both electrically isolate the cell from the mounting structure, and to take up some of the expansion of the pressure vessel that occurs on charging.

The sleeves are all mounted together in various ways. There are top attachments between these mounting sleeves; there are bottom attachments to make it a fairly rigid package. Every sleeve has a foot that overlaps the mounting foot of the other sleeve, so it minimizes the total mounting points of this battery. Nonetheless, we still have 34 inserts that we have to add into the spacecraft panel to handle this thing.

The baseplate is attached to all these sleeves. The baseplate is riveted to a ring at the bottom of those sleeves, and that provides for adequate thermal contact. In addition, that baseplate is optimized to provide the right kind of thermal gradient along the battery.

We had a bit of difficulty with the radiator which we are using for the battery, since it is physically sized for the nickel-cadmium battery and has to remain compatible with that. So the baseplate had sort of a graduated conductivity over its area to handle that and to conduct heat from cells that are on the perimeter of the battery toward the center of the battery. This is simply done by things like lightening holes, etc.

We have a basic conduction path through the sleeve, through the baseplate, through the spacecraft panel to the OSR radiator, and up through space. We have heaters, one of which is shown on the batteries. It is a thin filament heater that is glued to the sleeve.

On top of the battery we have a thermal cover to isolate it from the rest of the spacecraft, and a thermal skirt around the outside for the same purpose.

There is a little box behind one of the front connectors there (strain gauge electronics). It is an integral part of the battery. It is a very lightweight electronics package, about 100 grams, and provides power for the strain-gauge bridge on a lot of the cells. It takes it directly off the battery terminals, conditions it, supplies it to the strain-gauge bridge, takes the signal from the strain-gauge bridge, and converts that into a voltage that is somewhat similar to a cell voltage and then feeds it into that 28th channel.

So, as far as the spacecraft telemetry system is concerned, it thinks it is just looking at battery cell voltage, and that signal has to be further conditioned on the ground to convert it to the pressure for a capacity.

(Figure 6-30)

This slide summarizes a few of the physical properties, length, width, height, and weight. That's a lot there. Weight is actually a slightly bit higher now that we have our engineered models. One reason is the condition of that thermal cover that I mentioned. We are about 30.1 kilograms right now. The nickel-cadmium battery weighs about 32.5 kilograms, as Armantrout showed yesterday, so we are saving about five kilograms per spacecraft. So you can see it is not spectacular, but it is significant.

In the next slide, I have summarized some of the weight data.

(Figure 6-31)

It still shows 30.01 kilograms total. The cell breakdown is typical of the Intelsat design. I won't go into that too much. The total weight is about 890 grams. We are doing slightly better there in terms of energy per unit weight than we did for the NTS-2 design.

The battery assembly adds approximately six kilograms to that cell weight, and that's considerably more than you will typically find on your nickel-cadmium battery.

These little aluminum sleeves, while they are lightweight, there are 27 of them and that will raise something. So we are really paying a bit of a penalty here for the packaging inefficiency of the nickel-hydrogen cell. In spite of that though, we are still saving some weight.

(Figure 6-32)

This slide shows the Intelsat cell design that has been talked about here several times. What I need to highlight here is its simple design. It has been built successfully by Eagle Picher. It goes together without any great difficulties. It is pretty much foolproof. We haven't really had any major problems with getting the thing assembled so far.

It is a new thing to do this assembly on a flight program. We are doing a lot more control on all the components and on all the processes than we did on NTS-2. In most areas we have had some iterations and some difficulties. It has been very successful.

The engineering model cells that we are testing right now have shown performance generally better than what we were used to with NTS-2.

(Figure 6-33)

This slide summarizes some data on that. When we get these cells at Ford, we do some validation testing involving capacity measurements at 0°C, 10°C, and 20°C. Charging at 0°C is done at 1.5 amperes. Discharges are at 15 amperes. At 10 to 20 degrees, the charging is done at three amperes and discharge at 15 amperes.

The results you see here are interesting. The capacity is better at 0°C than at 10, there it's better than 20. On NTS-2 the capacity at zero and 10 were about identical. I guess it might have been slightly less at zero.

This performance is just excellent. The distribution is fairly tight. The charge voltages are, as we expected, a bit higher than what we see on the nickel cadmium. With the 27-cell package, we stay well within the system capability.

Another very interesting point is the cell discharge. We do a cell discharge test where we charge the cells up with three amperes for 16 hours, let it sit on open circuit for 72 hours, and do a capacity measurement. Typically in the past in nickel hydrogen you would expect to see about 70-percent capacity at that point.

We have consistently been measuring about 80 percent on these Eagle Picher engineering model cells of that original capacity. I am not totally sure why, we were very pleased with it, they were very tightly built, and I think things like cleanliness or just keeping plates clean during assembly, avoiding any possibility for getting minute metallic particles in there, whatever. That is all considerably better now than it has ever been. I think that is something that contributes to this good performance.

We will continue to work on the five additional batteries. Next year there ought to be a presentation on the results of that effort, and I hope some test data on it for flight batteries that will have been built by that time.

## DISCUSSION

THIERFELDER: You only have one strain gauge on 27 cells. Does your data show that your pressures are that uniform and a sample of one is enough?

VAN OMMERING: The pressures are not as uniform as you would like them to be.

There are some minor variations between cells, primarily due to capacity variations. When you make a stack you will find, as I show, a standard deviation of maybe an ampere-hour between cells. That capacity variation will translate into some pressure variations.

So all we are really doing here is getting an idea where the battery is at and what the state of charge is at of one cell. Now, we know what cell that is and we have a pretty good idea of what the state of charge is over the entire battery.

But it continues to be an estimate. It is not an exact indication for the whole battery.

THIERFELDER: If you lose that telemetry point, you don't feel that is critical?

VAN OMMERING: We are using that in this program purely for information. We are not using it for charge control. But we might. We have that extra channel available, so we put it on, but we don't need it for our control purposes.

The baseline approach for the nickel-hydrogen battery charge control is the same that we are using for nickel cadmium. While the baseline is the same, we don't know for sure what that baseline is.

ROGERS: On the strain gauge, our experience has been that we get a slow continual upward drift in absolute pressure as a function of time and cycling.

I am wondering whether you have noticed that, and whether your state of charge indication – or if you can use it for control – can take that into account?

VAN OMMERING: At COMSAT Labs, there has been quite a bit of testing done on these strain gauges, and I think occasionally we did see some.

Joe Stockwell would probably be the one to comment on that, since I suspect he's got that at his fingertips. But right now, our current cells, we have strain gauges installed, we are looking at them on these engineered models but, we have not been testing them long enough to draw any conclusions from this particular pressure cell.

ROGERS: It is not the strain gauge that drifts, it is the cell?

VAN OMMERING: Yes. I know what you mean.

STOCKWELL: Howard, yes, indeed. I think I showed some of that data from the NTS-2 here last year, where we do see an upward increase in pressure in the cell with time. It does show up with the strain gauge.

MAURER: You are saying that you are saving five kilograms going with nickel hydrogen, compared with nickel cadmium.

I assume that is based on the engineering model weights? And if so, are you assuming the same watt-hours delivered in both cases at the design maximum?

VAN OMMERING: Yes, that's correct. We have the same watt-hours delivered.

The weights are based on the engineering model.

The power that needs to be delivered is controlled by the spacecraft. The reason we are doing a bit better here is that we are going to deeper DOD, and that is where most of the gain comes from, deeper than we go on the NiCad. The NiCad limit is 55, and nickel hydrogen limit is 70. We have a little bit of margin built into both of them. Nickel hydrogen always runs about 10 percent deeper.

I would like to add something to that. The design we are dealing with now, diameterwise the cell is 3.5 inches, which is a pretty traditional thing. And that's really a design that's optimized for 50- to 70-ampere hour size. The 35-ampere-hour, 30-ampere hour battery cells would be much better off weightwise if you went to something like a 2.5- or 3-inch diameter. The weight savings involved in that are significant. But at this point we wanted to get this technology on the spacecraft, we don't want to fool around with trying to make new pressure vessels. That is a whole new ball game that would take several days to develop.

So we stuck with what was available, and we are paying a little bit of a penalty, but we would like to prove the technology in a real environment. That is what we are interested in now. We will handle weight improvements in the next generation.

DUNLOP: One thing that is interesting about the data that Van Ommering showed is capacity as a function of temperature. You will notice for the nickel-hydrogen batteries, you are actually drawing from about 32 or 33 ampere-hours, I think, at 22°C; after about 35 ampere-hours at 0°C, and about 34 ampere-hours at 10°C.

If you look at the nickel-cadmium battery, you get the opposite effect. You have got about 35, 36, 37 ampere-hours at 20°C, and you drop down to about 32 ampere-hours at 0°C.

So, when you talk about DOD, one of the things you run into is DOD at what temperature?

It turns out this particular spacecraft is operating at somewhere between zero and 10 degrees when they finally figure out where it is going to be during discharge. It might just be that it is not exactly easy to prepare DOD. The way the capacity as a function of temperature is turning out, it may be that there isn't much difference.

MUELLER: On your last vugraph, you had a column that was labeled range. Is that the spread in voltage among the cells when you have applied an average voltage shown in the first column? Is that what that entry means?

VAN OMMERING: I didn't really elaborate on that, what that whole charge of all this data means.

For one thing, it is a peak charge voltage of battery cells. The charge will roll over in a voltage cell. It is the peak voltage we are concerned with. The system has to be able to handle it, so that is one thing it shows, peak voltage.

The range shows the total variation in these charge voltages within a lot of cells, so I show 15 millivolts, for example, at 0°C. That means the difference in the charge voltage at that peak from cell to cell was 15 millivolts.

Now, when we take those cells and select out of that a set of cells to build a battery with, we have got material for the matching of that voltage to about six millivolts. So we take 40 cells, take 27 out of them; in that group of 27 the maximum is about 6.

MUELLER: 50 millivolts is for a lot, rather than for a battery complement of 27 cells.

VAN OMMERING: That's right.

FORD: You are carrying nickel cads along in parallel with nickel hydrogen.

The question I have is what criteria, or what had to come about before the final decision is made as to which way you go? And how long before the launch data of that satellite does that decision have to be made?

VAN OMMERING: No question about it, but I can't speak for Intelsat and COMSAT. Of course, we may run into surprises with nickel hydrogen, but what we have seen so far has been good. It will be a decision, I imagine, the recommendation by Ford to Intelsat, and it will have to be seriously considered by Intelsat.

If they go along with it, we will fly nickel hydrogen. But we plan to make that decision shortly before the first launch, and we are going to look very hard at the life-test data in particular, compare that with the data that we have on the Intelsat-V NiCad batteries. And we are going to do a very thorough analysis because we do always have to look at minimizing risk.

There certainly is a risk involved. We don't have seven years of testing on these batteries.

FORD: A followup question is, how many equivalent years? If you are doing accelerated tests, how many equivalent cycles do you expect to have when you make that decision?

VAN OMMERING: There are three life tests we are doing: One is done on engineered model cells and that is designed to give us a total capacity turnover on these battery cells. Equivalent to 10 years initially, it is going to be about 12 or 13 years at the provided time that we might launch that F5 spacecraft.

We are doing life test and accelerated life test or semiaccelerated life test I should call it, on one of the 12 batteries. That one is going to go on eclipse cycling, but we will accelerate it, if that is the right word, the solstice seasons. In other words, we are going to shorten them to something like 14 days.

That is probably a fair test because we have not really found a purely time-dependent or strong time-dependent degradation for the nickel hydrogen yet. By the time we launch the first spacecraft, I suspect we will have something like probably five or six full eclipse seasons completed on that.

In addition, we would like to have a full year of real-time testing on the other qual battery at COMSAT:

LEAR: Gert, that one slide you just showed up there when you compared the nickel hydrogen to the nickel-cadmium system, that was for the first season. How many seasons have you completed so far, and have you seen those curves drawing in?

VAN OMMERING: That is a real-time test, so that data isn't coming out very fast. I think we are about to start the second season of eclipse cycle.

LEAR: How does the data compare with the first season?

VAN OMMERING: Maybe John can answer that.

ARMANTROUT: That was just completed in the last week here. We haven't totally reduced it, John, but there is no trend that indicates anything is any different, just looking at it on a daily basis.

LEAR: One final question. What are you using for charge determination control?

VAN OMMERING: On the tests that we are doing, we are simply doing it on a time basis. On the spacecraft, I think there is still a final decision to be made on exactly what will be done in terms of charge control.

Ford's baseline is to use the bisequence charging scheme; five minutes on, five minutes off, and base the charge cutoff period on time. This isn't really based on what we would like to do for nickel cadmium. As I said with nickel hydrogen, we really don't have more information to try to decide on, as to when to terminate charge.

If that strain gauge business works out real well, I think we can minimize the charge and use that consistently.

BETZ: Gert, on the life test are you charging with the bisequence charge?

VAN OMMERING: On our accelerated life test we do not. That's the only one we have done so far. On that other life test, yes, we are using that, the one I showed the voltage data on.

BETZ: Are you reconditioning your nickel-hydrogen batteries between seasons on your life test?

VAN OMMERING: Yes. I think we take that right along with the nickel-cadmium battery. We are treating them exactly the same. I don't think it is benefiting us a great deal on that NTS-2 prototype, but we are doing it.

This is the first time anybody is going to have decent comparative data between NiCad, nickel hydrogen, same capacity, same operation.

BETZ: What is the thickness of your aluminum sleeves on the Ford battery?

VAN OMMERING: It is optimized to give us proper thermal control and sufficient mechanical strength. We are running typically 40 mils on that.

BETZ: The NTS-2 nickel-hydrogen batteries in orbit right now have a total voltage range of about 21 millivolts over 14 cells after 2 1/2 years in two of the assemblies on opposite sides of the satellite, so there are some temperature differences.

I still think our voltage range hasn't changed but about 7 millivolts since launch.

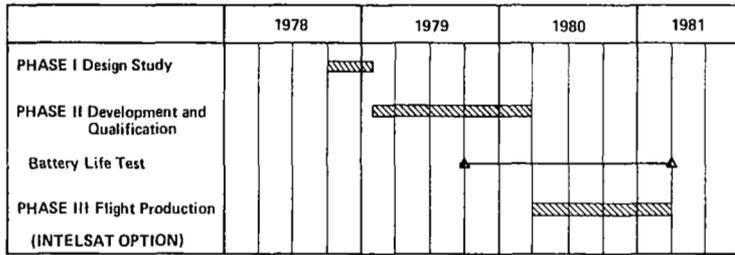
MAURER: This question is to any of the nickel-hydrogen types in the audience. Is there any data on nickel-hydrogen cells at elevated temperatures? In other words, life data?

VAN OMMERING: No.

Maybe Hughes has some, but as far as I know COMSAT, Intelsat really haven't done any long-term life tests above 20°C. I think there have been some life tests run on boilerplate cells just sitting in a room. The summers in the Washington are can be hot, the energy problems, the air conditioning isn't doing all that well. So I think 25 degrees for half of the year is probably the worst we have ever seen.

LEAR: I don't speak for Hughes, but they do have tests for high temperatures. But, Howard left to get an airplane.

## NICKEL-HYDROGEN BATTERY SCHEDULE



 Ford Aerospace & Communications Corporation

Figure 6-22

## NICKEL-HYDROGEN DESIGN ADVANTAGES

### NEGATIVE ELECTRODE NOT SOLUBLE IN ELECTROLYTE

- IMPROVED LIFETIME STABILITY
- NO MIGRATION
- NO RECRYSTALLIZATION
- RELATIVELY INSENSITIVE TO DOD (CATALYTIC SURFACE) - HIGHER USABLE ENERGY DENSITY

### SEPARATOR (ASBESTOS)

- CHEMICALLY STABLE
- INHERENTLY WETTABLE

### ELECTROLYTE SURPLUS

- NO DANGER OF OVERPRESSURE
- NO DANGER OF DRYOUT AT CHARGE RATES EXPERIENCED ON SYNCHRONOUS ORBIT
- HIGHER ELECTROLYTE INVENTORY-MORE HYDROPHYLIC SEPARATOR

### START-OF-CHARGE INDICATION

- PRESSURE DIRECTLY PROPORTIONAL TO SOC CAN BE MEASURED BY STRAIN GAGE

### POSITIVE ELECTRODE

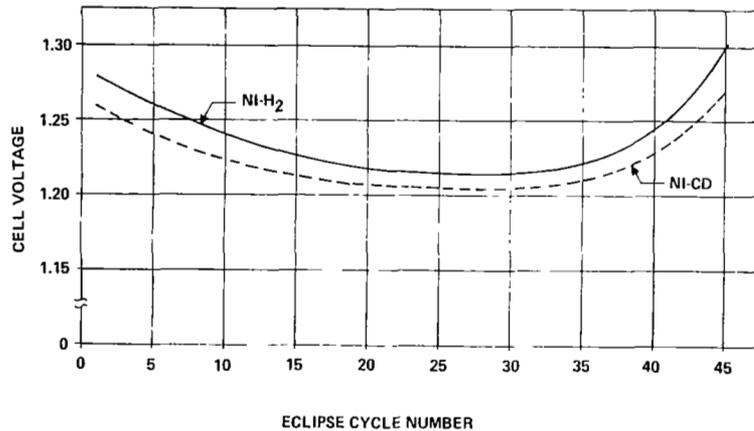
- ELECTROCHEMICALLY IMPREGNATED-INCREASED UTILIZATION REDUCES ELECTRODE EXPANSION

 Ford Aerospace & Communications Corporation

Figure 6-23

## ECLIPSE DISCHARGE VOLTAGE

BATTERY ECLIPSE SEASON ONE



 Ford Aerospace & Communications Corporation

Figure 6-24

## GENERAL CHARACTERISTICS OF NICKEL-HYDROGEN

- SPACECRAFT INTERCHANGEABILITY OF NICKEL-HYDROGEN AND NICKEL-CADMIUM BATTERIES
- TWO 30 Ah, 27 CELL ASSEMBLIES
- STRAIN GAGE CELL PRESSURE MONITORING (ON ONE CELL)
- INTELSAT CELL DESIGN
- 70 PERCENT DEPTH OF DISCHARGE MAXIMUM LIMIT
- AUTOMATIC LOW TEMPERATURE HEATER CONTROL
- MULTIPLE CHARGE RATE CONTROL SYSTEM
- BATTERY RECONDITIONING CAPABILITY

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Figure 6-25

## NICKEL-HYDROGEN BATTERY ASSEMBLY PERFORMANCE CHARACTERISTICS

CHARACTERISTIC	VALUE
TOTAL ELECTRICAL BUS LOAD	911.5 W
MAXIMUM DEPTH OF DISCHARGE (% OF ACTUAL CELL CAPACITY AT 1.18 V AVERAGE)	59.0% DURING ECLIPSE OPERATION
ACTUAL CELL CAPACITY	30.0 Ah
NOMINAL DISCHARGE CURRENT	14.3 A
MAXIMUM DISCHARGE TIME	1.2 HOURS
FULL CHARGE CURRENT (EOL, EQUINOX)	2.39 A
TRICKLE CHARGE CURRENT (EOL, SOLSTICE)	0.71 A
TOTAL CYCLES AND ECLIPSE (7 YEARS) (616 ECLIPSE CYCLES + 175 ETT FIRINGS)	791 CYCLES
ORBITAL LIFE	7 YEARS
BATTERY CONFIGURATION (2 BATTERIES PER SPACECRAFT)	27 CELL ASSEMBLIES
NOMINAL BATTERY HEAT OUTPUT DURING OVERCHARGE, AVERAGE	50 W (EQUIVALENT)
ALLOWABLE BATTERY TEMPERATURE RANGE DURING ORBITAL OPERATION (THERMISTOR MEASUREMENT)	+1.0° TO +25.0°C
MAXIMUM BATTERY CHARGE VOLTAGE	42.3 V
MINIMUM BATTERY DISCHARGE VOLTAGE (WITH ONE CELL FAILED)	29.7 V

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Figure 6-26

## BATTERY TELEMETRY

- 27 battery cell voltages
- Battery pressure - strain gage bridge (uses 28th voltage channel)
- Battery temperature - thermistor

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Figure 6-27

## NICKEL-HYDROGEN BATTERY EQUIPMENT PLATFORMS

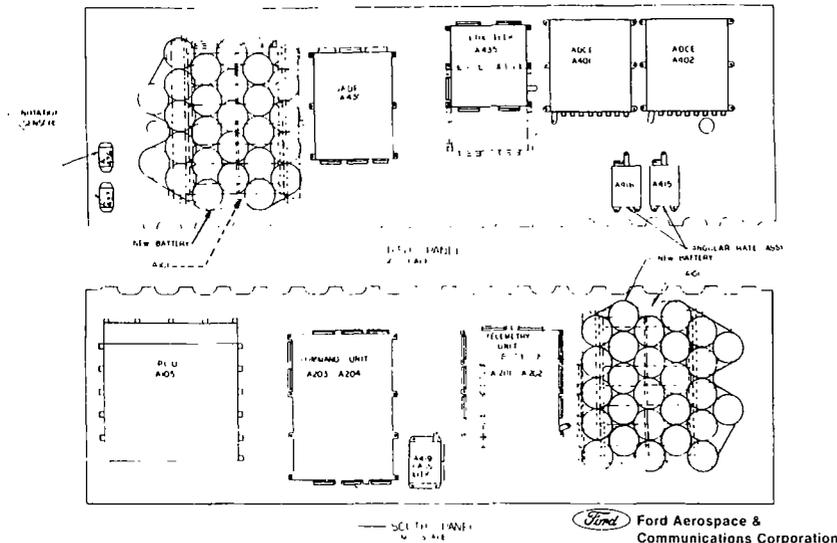


Figure 6-28

## NICKEL-HYDROGEN BATTERY CONFIGURATION

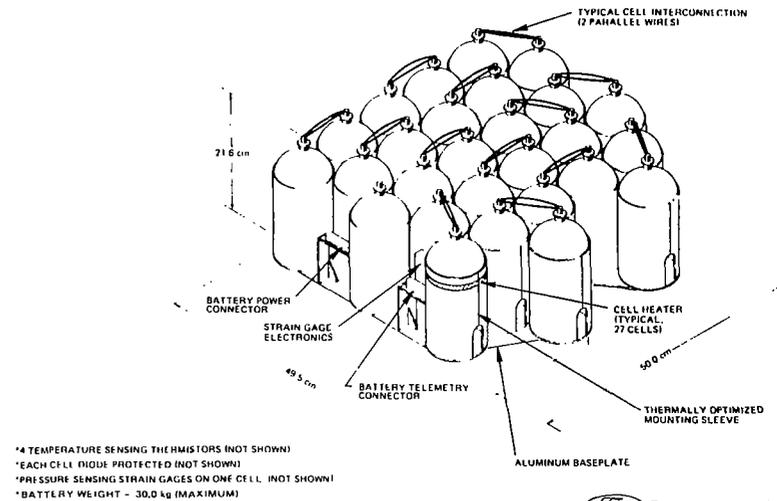


Figure 6-29

## NICKEL-HYDROGEN BATTERY PHYSICAL PROPERTIES

- Length 52.07 cm
- Width 51.82 cm
- Height 22.15 cm
- Weight 30.01 kg

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Figure 6-30

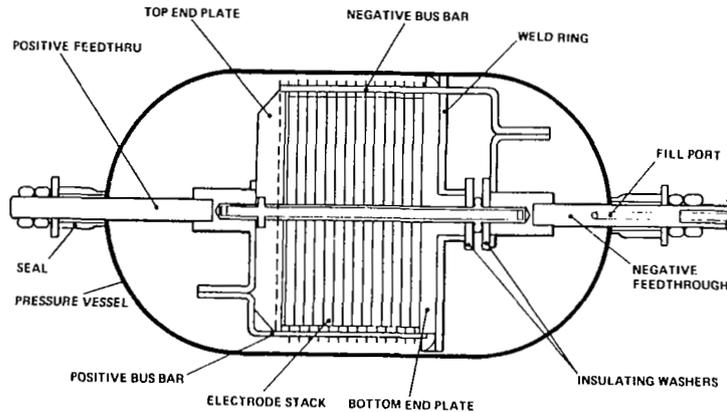
## NICKEL-HYDROGEN CELL AND BATTERY WEIGHTS (ESTIMATED)

	Quantity	Unit Weight (g)	Total Weight
<b>Battery Cell Assembly</b>			
Positive electrodes	24	12.3	295g
Negative electrodes	24	2.0	48
Separator	24	1.1	26.5
Screws	13	0.5	6.5
Electrolyte	A-R		50
Insulators	2	17	34
Proton pump	1	243	243
Mechanical hardware	A-R		147
Total cell weight			690 g
<b>Battery Assembly</b>			
Battery cell assembly	27	950	24.03 kg
Fast mounting shells	27	125	3.38
Baseplate	1		0.65
Endcap assemblies	27		96
Mounting hardware	A-R		10
Connectors, heaters, thermistors, and strain gauges	A-R		0.23
Microprocessor/telemetry interface	A-R		0.66
Battery assembly weight			30.01 kg

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Figure 6-31

## INTELSAT NICKEL-HYDROGEN CELL DESIGN



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Figure 6-32

## ENGINEERING MODEL CELL PERFORMANCE

TEST	TEMPERATURE (°C)	CAPACITY (Ah)		CHARGE VOLTAGE (V)	
		AVERAGE	STD DEV	AVERAGE	RANGE
CAPACITY	0	35.34	1.13	1.540	0.015
CAPACITY	10	34.80	1.04	1.524	0.018
CAPACITY	20	32.06	0.89	1.506	0.018
72-HOUR SELF DISCHARGE	10	28.52	0.52		

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Figure 6-33



## AIR FORCE NICKEL-HYDROGEN FLIGHT EXPERIMENT

L. Miller  
Eagle Picher

The Air Force experiment data has been presented before, and because of the rush in the program which necessitated us using existing nickel-cadmium battery technology and components, I think the time from inception of the program to launch was about 18 months.

It doesn't really incorporate the current technology that is available today. As I go over this, I will probably pass over some of these vignettes very quickly until we get to the summary of the data at the end.

What I think is important is to look at it from the standpoint that this was not a really good design. It had a lot of bad points. But the battery forgave any design problems that cropped up.

The program intent was, of course, to gain some actual flight experience on nickel hydrogen. It is supposed to be the first one launched, but I think the NTS-2 and the Air Force launched just about the same time.

The program was under the direction of Wright Patterson Air Force Base. Eagle Picher was the prime contractor for the first time I guess in the history of the business, and Lockheed Missile and Space Company was the subcontractor.

The mission wasn't of a long duration. It was about 8 months. It was launched on the Air Force low-Earth orbit satellite as an experiment in one of the pilots.

(Figure 6-34)

I was going to say the cell on your right, but now I am going to say the cell on the top. It is the actual Air Force cell, and it has a rather narrow cover design. It uses an Inconel 625 pressure vessel. The little capsule in there is the module for attachment of the strain gauge.

Internally, it features what is referred to as the Air Force pineapple stack design. However, it doesn't have the most current technology, and basically the recirculation mechanism is in wall-wick configuration.

I might mention the smaller cell just below it. That was the cell manufactured for the Navy NTS-2 program, that basically features the COMSAT laboratory design technology.

Actually the cell we are manufacturing now for Ford looks very much like that. The difference is about a quarter inch shorter.

(Figure 6-35)

With respect to cell design features – this just touches upon Hughes’ design characteristics. Fifty-five ampere-hour electrochemically impregnated nickel electrodes. This was manufactured on the Bell impregnation line which was still in operation at that time, in Joplin.

Teflonated platinum catalytic electrodes and the separator were EPI reconstituted asbestos. The gas spacer – I think that’s an error – was actually switched over in the final cell designs to a Vexar polypropylene material. The cell casing is hydroformed Inconel 625, dual plastic seals.

(Figure 6-36)

The cell acceptance testing was pretty much what you see in nickel cad: some four 100-percent cycles, charge retention, electrolyte leakage, fuel cycle test, electrolyte leakage.

(Figure 6-37)

With respect to the battery itself – this is view of the battery – it is upside down. Actually, this is the way it was mounted in the spacecraft. It is an aluminum cased configuration. The heater blanket is attached on the bottom of the system. That’s an area that also looked into space for coolant control.

(Figure 6-38)

Here is the same battery with cells mounted into it on the vibration going through qualification. A lower portion there, the copper colored component just for protection. That didn’t actually fly in orbit. It wasn’t part of the battery and did not fly on the mission.

The battery design features are shown in the next vugraph.

(Figure 6-39)

The number of cells was 21. It turned out the same approximate voltage as the 22-cell nickel-cadmium battery.

We monitored each cell voltage, one battery voltage. Current monitoring bipolar electrometric sensor. Again, the technology on these components are straight off the Eagle Picher nickel-cadmium battery.

The number of thermistors is 21. Each cell two batteries, two in the battery. For pressure monitoring, we had strain gauges on every cell. The heater is redundant; of course, redundant controllers. The total battery weight was 110 pounds. Again this was not intended to optimize the system with respect to weight.

(Figure 6-40)

I believe this is the acceptance test. Again, it is very similar to what you expect to do on nickel-cadmium battery dielectric thermistor insulation, current sensor, some capacity cycling, dimensional pressure, inert gravity.

May I have the next slide which shows the qualifications.

(Figure 6-41)

Again, this is patterned after nickel cadmium. Acceleration thermal random, sinusoidal, mechanical pyrotechnic, thermal vacuum cycling. Then, there is this special thermal vacuum because it turned out to be a thermal design in the system. We didn't have a variable window looking out into space, and there was real concern that the battery would get too cold after it was launched before we would go into operation.

It turned out it was able to endure this low-temperature exposure without damage.

(Figure 6-42)

This is a diagram of how the battery was mounted on the pallet. Three major components include the battery, control assembly, and the variable load bank.

The technology I considered primitive. The battery was controlled by a single-level voltage geared to bring the voltage cell to 90-percent state of charge at a pressure of about 500 psig. There was no other means of changing anything on the battery if it proved necessary.

The thermal control designs were all fixed. We couldn't make any changes there except with the heaters. We could turn those off and on more frequently or as required.

(Figure 6-43)

As I indicated, the battery flew as an experiment, so we were restricted; limited in our use of the system based upon the power that was left over after the primary mission was served. So we didn't get a lot of cycles on the battery. However, the way it was used was for nickel cadmium. It created a serious problem because we had to go into a number of orbits to get the battery back up to charge, and that would vary with each cycle.

In the nickel cadmium, the power measurement people would have been completely lost with respect to where the battery was. However, with the pressure monitoring devices on the battery, they knew at all times the exact state of charge of the system.

The 1733, 7-percent DOD cycles were accumulated when the battery was actually supplying power to the primary mission. The 50-percent DOD cycles that were accumulated were accumulated using variable load bank. That was part of the experiment. Of course, 100-percent DOD cycle was used when we were using the variable load bank.

Four of the loads that were available, 10, 20, 30, and 40, could be used separately or just combined as you see in the last column there.

Maximum discharge rate was 75 ampere-hours and the 1.5 C rate.

Over on the last two columns, you can see how close the predicted capacity versus the measured capacity package. As you can see for the 10 ampere and the 20 ampere rate, what we predicted and measured were very close. Once you get into higher discharge rates, they start to drift apart.

What is going on here is that at these higher rates, the battery is hitting the cutoff voltage sooner. If you took it on down to a lower discharge rate, that brought those two predicted and measured pretty much back together again.

With respect to the thermal cycling of the system, as you see, the deltas were for the 20, 40, and 75-ampere hour rates. What might be of interest here is what actually happened. There were three batteries manufactured, and some of those underwent testing on the ground. The mechanical model was tested at Lockheed.

Again, although the designs certainly are not optimum, the way it was used was certainly not under the best of conditions. But the mechanical model at Lockheed, I understand now has gone through 6000 cycles at around 60-percent DOD and still seems to be performing very well.

I understand the thermal model battery is at Wright Patterson. I have no information on what testing was done on that.

Again, a point I want to make is that although it is certainly not elaborate testing of the system, we did get very good data. We are satisfied with the results of the program. We didn't see any incipient problems with the use of nickel hydrogen in space, and it pretty much followed the preflight predictions. Overall I think we are very satisfied with this program.

## DISCUSSION

DUNLOP: What was that cutoff voltage?

MILLER: I think the cutoff voltage was around 149. I'd have to check that for sure.

DUNLOP: How did that limit your discharge capacity?

MILLER: It didn't. That was just the charge cutoff. They fixed one level charge cutoff point.

DUNLOP: When you showed a 75-ampere discharge rate, you showed the capacity dropping down to 34 ampere-hours. I guess I didn't understand that point.

MILLER: That was just the cutoff on the voltage which I think was also established at about 1.1 volts per cell. That circuit undervoltage protection could be disabled to allow it to go down.

I mentioned also the battery was reversed twice. Once intentionally and once in error during the mission, and we haven't suffered any damage.

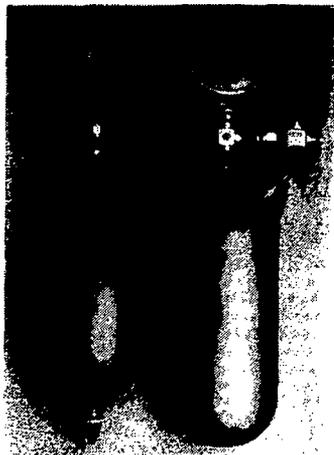


Figure 6-34

RNH-50-9

CYLINDRICAL CELL DESIGN FEATURES

CAPACITY	55 AH
CATHODE	ELECTROCHEMICALLY IMPREGNATED NICKEL ELECTRODE
ANODE	TEFLONATED PLATINUM CATALYTIC ELECTRODE
SEPARATOR	EPI RECONSTITUTED ASBESTOS
GAS SPACER	WOVEN TEFLON
CELL CASE	HYDROFORMED INCOHEL 625
TERMINAL SEAL	DUAL-PLASTIC COMPRESSION

Figure 6-35

CELL ACCEPTANCE TESTS

GAS LEAKAGE TEST	10 <sup>-8</sup> cc/sec @ 250 PSIG		
CAPACITY TEST @ C/2	CHARGE RATE	TEMP	CAPACITY
	12.5 AMP	68°F	48.8 AH
	3.0 AMP	68°F	51.2 AH
	12.5 AMP	45°F	51.2 AH
	3.0 AMP	45°F	52.5 AH
DISCHARGE FROM 1.0 TO 0.0 VOLTS	21.2 PSIG		
CHARGE RETENTION TEST	39.2 AH AFTER 48 HOURS		
ELECTROLYTE LEAKAGE TEST	NONE		
CYCLE TEST	52.9 AH @ 6TH CYCLE		
ELECTROLYTE LEAKAGE TEST	NONE		

Figure 6-36



Figure 6-37

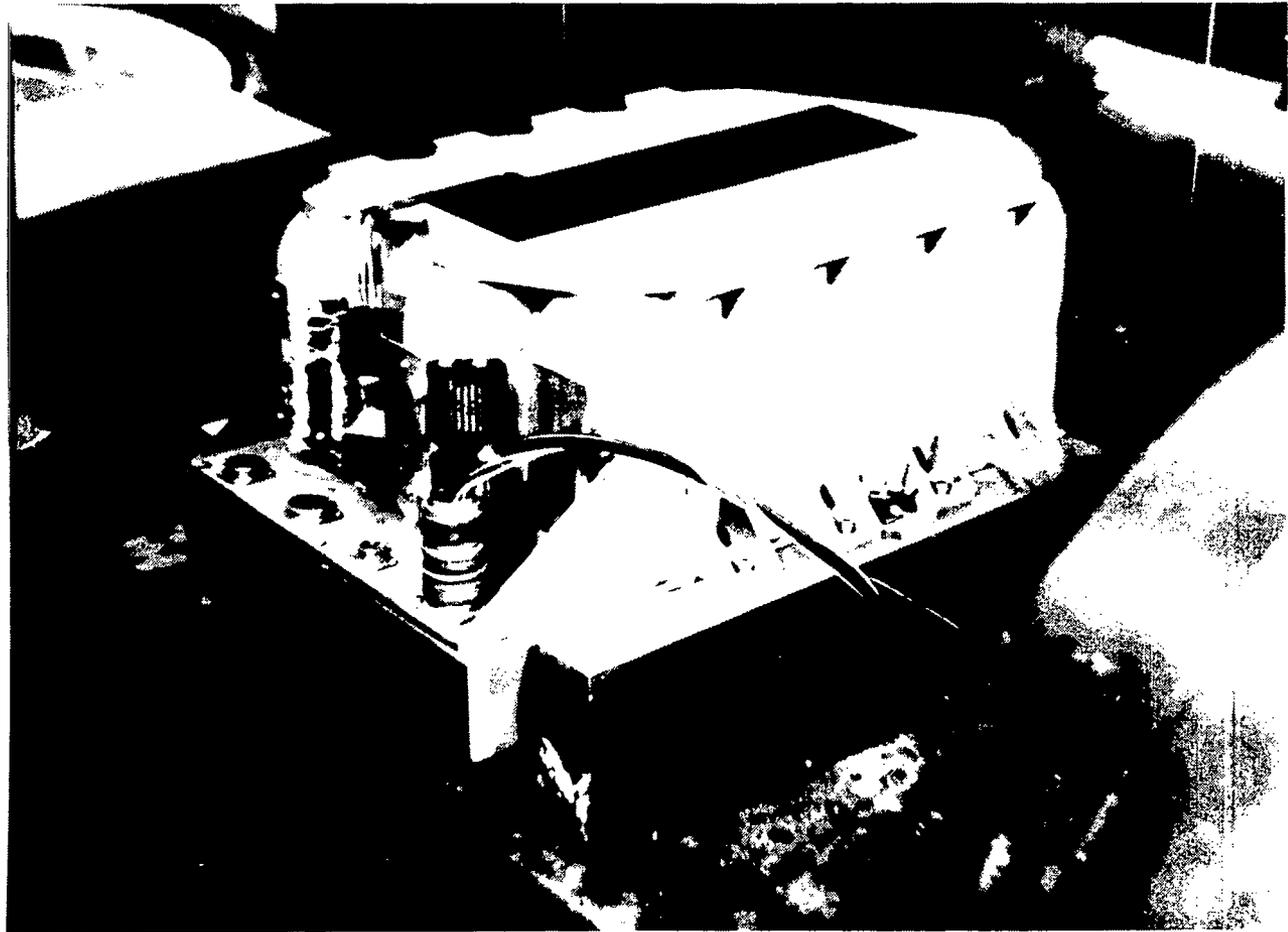


Figure 6-38

SAR-10005 BATTERY DESIGN FEATURES	
- NO. OF CELLS	- 21
- BATTERY STRUCTURE	- INVESTMENT CASTING ALUMINUM A-356-T61 ALLOY
- VOLTAGE MONITORS	- 21 INDIVIDUAL CELLS 1 BATTERY
- CURRENT MONITOR	- BI POLAR ELECTROMAGNETIC SENSOR (20 AMPS CHARGE - 50 AMPS DISCHARGE)
- TEMPERATURE MONITORS	- THERMISTORS (21 CELLS - 2 BATTERY)
- PRESSURE MONITORS	- STRAIN GAGE - 21 CELLS
- HEATERS	- REDUNDANT PHOTOETCHED
- HEATER CONTROLLERS	- REDUNDANT SOLID STATE
- BATTERY WEIGHT	- 110 LB

Figure 6-39

BATTERY ACCEPTANCE TESTS	
VISUAL INSPECTION	
WEIGHT CHECK	110.0 LBS
DIELECTRIC TEST	10-20 MEGOHMS @ 250 VDC
THERMISTOR TEST @ 77°F AND 40°F	
INSULATION RESISTANCE TEST	50 MEGOHMS @ 50 VDC
STRAY VOLTAGE CHECK	LESS THAN .05 VOLTS
CURRENT SENSOR TEST @ 12.5 AMPS CHARGE, ZERO AND 25.0 AMPS DISCHARGE	
TEMPERATURE SENSOR TEST @ 40 AND 77°F; EXCITATION VOLTAGE 24, 28.5 AND 33 VDC	
CAPACITY TEST @ C/2	68°F - 50.0 AH 40°F - 51.7 AH
HEATER TEST	PRIMARY HEATER ON - 41°F BACK-UP HEATER ON - 36°F BACK-UP HEATER OFF - 38.6°F PRIMARY HEATER OFF - 44.3°F
DIMENSIONAL CHECK	
PRESSURE SENSOR CALIBRATION CHECK	
C.G. DETERMINATION	
INSTRUMENTATION & HEATER BUS POWER CONSUMPTION CHECK	

Figure 6-40

BATTERY QUALIFICATION TESTS

ACCEPTANCE TESTS

ACCELERATION TEST	15 G FOR 5 MINUTES (3 AXES)								
THERMAL SHOCK	-20°F TO +115°F								
RANDOM VIBRATION	12 G RMS FOR 5 MINUTES (3 AXES) 0.1 G <sup>2</sup> /Hz								
SINUSOIDAL VIBRATION	7.5 G FOR 25 MINUTES (3 AXES)								
MECHANICAL SHOCK	30 G; 1/2 SINE WAVE; 11 ms								
PYROTECHNIC SHOCK	2600 G PEAK ACCELERATION; 200 - 10 <sup>-4</sup> Hz								
THERMAL-VAC PERFORMANCE TEST	10 <sup>-4</sup> TORR @ 32°, 59° AND 86°F <table border="0" style="margin-left: 20px;"> <tr> <td>CHARGE</td> <td>DISCHARGE</td> </tr> <tr> <td>5.0 AMPS</td> <td>50.0 AMPS</td> </tr> <tr> <td>25.0 AMPS</td> <td>25.0 AMPS</td> </tr> <tr> <td>50.0 AMPS</td> <td>5.0 AMPS</td> </tr> </table>	CHARGE	DISCHARGE	5.0 AMPS	50.0 AMPS	25.0 AMPS	25.0 AMPS	50.0 AMPS	5.0 AMPS
CHARGE	DISCHARGE								
5.0 AMPS	50.0 AMPS								
25.0 AMPS	25.0 AMPS								
50.0 AMPS	5.0 AMPS								
THERMAL-VAC CYCLE TEST	10 <sup>-4</sup> TORR @ 40°F 30.0 AMP CHARGE FOR 55 MINUTES 42.8 AMP DISCHARGE FOR 35 MINUTES 32 SIMULATED ORBITS, 50% DOD								
SPECIAL THERMAL-VAC TESTS	INSTRUMENTATION POWER DISSIPATION HEATER CALIBRATION SPECIFIC HEAT MEASUREMENT CHARGE EFFICIENCY VS. TEMPERATURE STATE-OF-CHARGE CHARGE CURRENT SIMULATED 90 MINUTE ORBIT CYCLES								

Figure 6-41

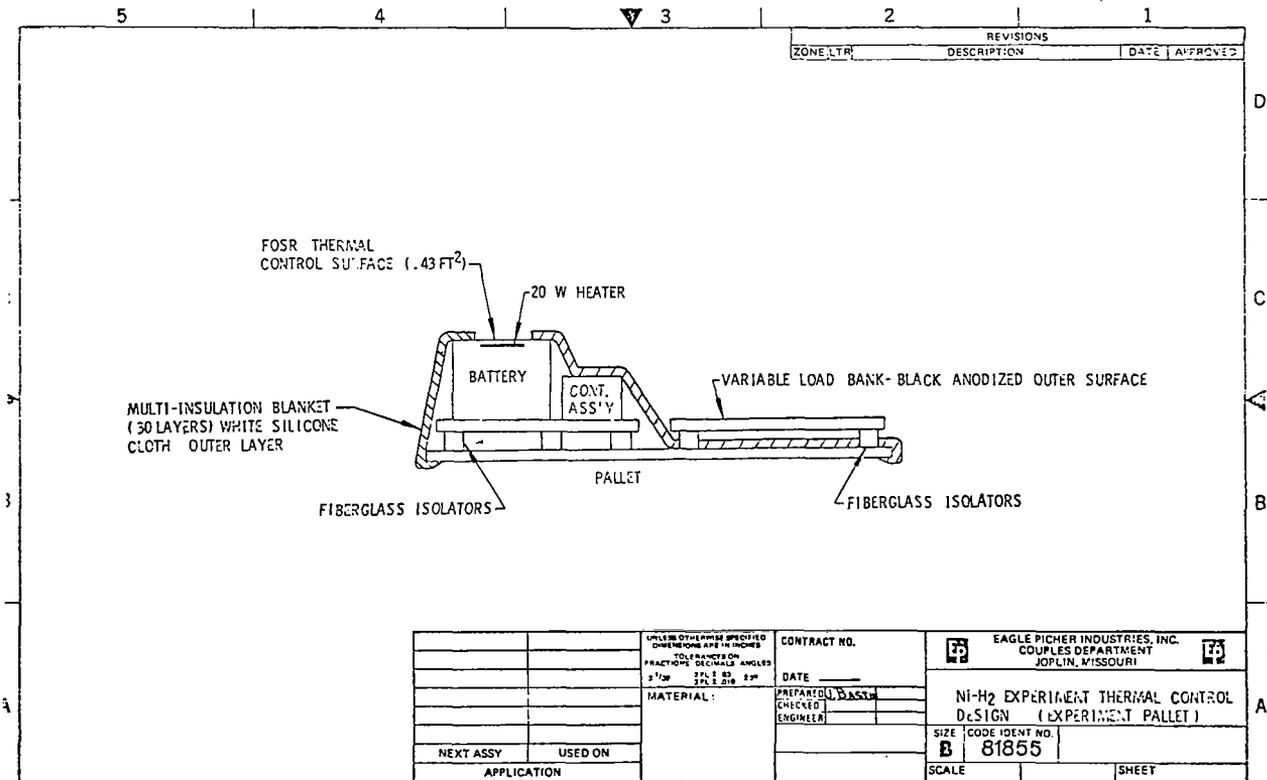


Figure 6-42

7% DOD (1,733 CYCLES) 4.6 A RATE:

TYPICAL DISCHARGE VOLTAGE CYCLE - 30.4 V TO 29.0 V

TYPICAL DISCHARGE TEMPERATURE CYCLE - 42°F TO 46°F

TYPICAL DISCHARGE PRESSURE CYCLE - 495 PSIG TO 470 PSIG

50% DOD CYCLE (26 CYCLES) 5.0 A RATE:

TYPICAL DISCHARGE VOLTAGE CYCLE - 30.6 V TO 27.4 V

TYPICAL DISCHARGE TEMPERATURE CYCLE - 42°F TO 48°F

TYPICAL DISCHARGE PRESSURE CYCLE - 495 PSIG TO 270 PSIG

100% DOD CYCLE (6 CYCLES):

<u>DISCHARGE RATE</u>	<u>MID-POINT DISCHARGE VOLTAGE</u>	<u>PREDICTED CAPACITY (PRESS)</u>	<u>MEASURED CAPACITY</u>
10 A	26.4 V	47.7 AHR	47.8 AHR
20 A	26.2 V	44.2 AHR	44.5 AHR
40 A	25.0 V	43.3 AHR	42.5 AHR
75 A	23.0 V	40.9 AHR	34.9 AHR

100% DOD CYCLE, THERMAL GRADIENTS:

20 A DISCHARGE RATE - INSIDE CELL (MAX)	71.3°F
OUTSIDE BATTERY (MAX)	<u>67.3°F</u>
GRADIENT	4.0°F
40 A DISCHARGE RATE - INSIDE CELL (MAX)	81.5°F
OUTSIDE BATTERY (MAX)	<u>73.1°F</u>
GRADIENT	8.4°F
75 A DISCHARGE RATE - INSIDE CELL (MAX)	85.6°F
OUTSIDE BATTERY (MAX)	<u>75.2°F</u>
GRADIENT	10.0°F

FIG. 8 - SPACE EXPERIMENT DATA SUMMARY

Figure 6-43

## NICKEL HYDROGEN CELL CHARACTERIZATION TEST RESULTS

B. Otzinger  
Rockwell International

I am going to present some of the nickel-hydrogen cell characterization test data that we collected during this last year. Our particular work this year was pretty much limited to charge control studies, or the kind of work that would be related to charge control.

The three areas that were covered were capacity versus temperature, our characterization; ampere-hour cycling efficiency; and charge method with respect to particular method. And the method was a voltage level with current limiting.

(Figure 6-44)

This first vugraph shows the characterization curves that we came up with for capacity versus temperature. The ordinate is capacity in ampere-hours, and we show the temperature degrees Centigrade on the abscissa. We have three curves shown here: One a typical nickel-cadmium curve; secondly, a Hughes cell, 50-ampere-hour cell from AF APL; and Eagle Picher nickel-hydrogen cell. That's a 35-ampere hour unit. It is the pineapple slice; it is an Air Force derived cell configuration.

We show the nickel cadmium here as a reference. All these three curves have all been normalized. That is, the data isn't necessarily 50 ampere-hours. It has all been normalized to 50 ampere-hours for comparison purposes.

Some points of interest. This is a different type of a characterization than you normally have; that you see people doing. That is characterizing a cell and/or an energy system where you are looking at capacity versus temperature. But it is one that shows a difference in character between nickel hydrogen and nickel cadmium which is kind of interesting.

We had heard from or we knew of the work at Hughes Aircraft, and they had indicated that capacity was improving with a reduction in temperature. This is one of the reasons we got into this investigation to begin with.

As we went lower with temperature, the capacity kept going up. So we went as far as we could go within the limits of our equipment. We couldn't get below 20 degrees. As a matter of fact, we didn't quite reach 20. I think we got to 18, and because of the means of mounting and cooling the Hughes cell, we couldn't get to minus 10. Unfortunately, with Eagle Picher's cell, we weren't able to increase the temperature because we had thermoelectric units cooling and there wasn't any way that we could maintain temperature control beyond 20°C.

A couple of things that come out as issues or have some interest or conclusions that you might reach.

One is the Hughes cell that is a 50-ampere-hour cell as far as nominal rating. But as you can see, we and most people that have been testing cells have been obtaining more like 40 ampere hours at 20°C. Don Warnock of APL got out a letter saying there was a deficiency in his line that they were correcting.

What is kind of interesting here is whatever the mechanism is that is causing this loss of capacity, it apparently is very temperature dependent, and as we go down in temperature, it approaches the Eagle Picher performance.

One of the issues that comes up is that nickel hydrogen, in general, falls off on capacity output as temperature increases. I think we have seen that on all the different designs.

The issue is, if you wanted to improve higher temperature performance, you might well be able to do it at the cost of your low-temperature performance, since it is performing so well at a temperature below what you would ever intend to operate at. There are things that could be done like the addition of cobalt hydroxide, maybe skewing the electrolyte concentration. There are numerous things that could be done that might work at a detriment to the low temperature, but may well shift the performance on the high end. And this is something that I know our project officers are upset about, and they would like to see better performances on the top end of nickel hydrogen.

This now indicates that we probably have a way, if we can determine a way of doing it effectively, it looks like there is a chance of working that out.

Another point that comes up is if we can improve the higher temperature, and this curve is so flat, the implication is that we may be able to do away with temperature compensation of the voltage level in the operation of nickel hydrogen, which would again be another improvement over the nickel-cadmium system. One of the chief reasons we do temperature compensation is that the nickel-cadmium system falls off so sharply as temperature goes down.

(Figure 6-45)

Something else that we looked at was the cycling efficiency. What we have here is an ampere-hour output on the ordinate, and ampere-hour input on the abscissa. Of course, you plot one against the other, and you come up with efficiency in terms of – I have it in terms of percent. It shows you range, 100 percent, 90 percent, and 80 percent. And along with that I have it in terms of C/D ratio.

The way we conducted this test is that we put a given amount at a rate – we have the different rates listed here – at the 50-ampere-hour rate, we put in on 45 ampere-hours, and we measured what we got out. We started on the low end and worked up, and likewise we started at the low rates and worked progressively to the greater rates.

One of the interesting things that came out of this, we charged as long as 80 ampere-hours on 50-ampere-hour units. We made sure that the overcharge was of such a nature that we got out all

that you could hope to get out of the cell. So this shows you your ultimate capacity out at given rates. Plus, of course, it shows you what efficiency you can expect at these various rates. As you can see, it is very rate sensitive.

At the 50-ampere-hour rate why we had very good efficiency right on up. At about 90-percent efficiency we got very close to rated.

(Figure 6-46)

We didn't get as far along with this work as I had hoped we would. But I do have a couple of plots here. What we show on this vugraph is cell-charge voltage versus temperature in degrees Celsius. This is a temperature compensation curve for a constant voltage system with current limit typical of what we are using on many of our spacecraft.

I worked for a current isogram. That is, we set our voltage by trial and error, came up with a constant residual or trickle current and plotted — we did this at various temperatures — and plotted the points and generated this curve. I put in a sample of a nickel cadmium, and you can see, we get very close correspondence. However, the nickel cadmium is generally set up to provide a constant ampere-hour output.

We were concerned about a constant trickle charge. The constant trickle charge is related to capacity and is very close to constant. Almost — it doesn't provide a constant capacity, but it very nearly does.

And at the very low, 0.6-ampere rate for the 50-ampere-hour unit; when we got to this region down here, the voltage for the recharge was so low that we didn't get enough charge return to recharge the battery. So I put an extended dotted line here. But, in fact, the values were so low that they were no longer useful. This is pretty much the minimum that you could work to.

Some of these currents are a little high with regard to what solar arrays normally like to put out. So that, in itself, is of some interest.

## DISCUSSION

LEAR: That first chart you showed where you did the characterization, what was the charge-discharge?

OTZINGER: I didn't mention that. We didn't try to experiment with any. We used what you might call an acceptance cycle. That is, we made certain that we got complete charge return.

(Figure 6-44)

C/10 for 16 hours, and that, by experience, is a value that always got us a full charge. Our discharge was C/2.

As I say, this was a very typical kind of operation. Each point was at least two cycles; in some cases, three and four.

One thing I didn't state that was kind of interesting. This point here, we continued on for about six cycles because we were amazed, the capacitors kept climbing. This is a plot of probably the second or third cycle capacity. But I believe we wound up, with normalization, around 68 ampere-hours. So we were still climbing.

I have asked some electrochemists the question, isn't this a surprise to see the nickel plate becoming more efficient on charge as temperature goes down?

And they said, yes it was. But apparently half-cell tests or that type of test isn't something that anyone has paid any attention to.

SCOTT: Can you say something about the end of charge voltages at these different temperatures?

OTZINGER: As might be expected, they went up. After minus 20 degrees, we were on 1.62. I was watching it carefully. I was getting a little alarmed as it was going up, but at 1.62 at minus 20, it was consistent and we weren't having any problems with it.

The temperature on the end of charge was going up uniformly. We weren't finding any dramatic behavior.

SCOTT: Also, do you know or did you calculate about what utilization of the positive material you were getting at minus 20, minus 10, or minus 20 degrees, and could not that increase in capacity simply be a growth in the actual utilization of the material that wasn't being used early in your cycling?

OTZINGER: That could well be. No, we didn't make that calculation. It is a good point.

MAURER: I want to comment on the capacity increase. That is not the difference between nickel hydrogen and nickel cadmium. It is the presence of the electrochemical positive.

A nickel-cadmium cell will do the same thing if you can make it with electrochemical positives. We used that as a final qualification test on a cell when we were making terrestrial batteries with electrochemical positives. It had to give higher capacity at lower temperatures. Otherwise, it was a reflection of an improperly made nickel electrode, and the lack of capacity increase resulted from corrosion of the sinter during impregnation giving you chemically deposited material in the pores, which massed out this capacity enhancement. If you eliminated corrosion entirely, then you got this big increase.

If you do potentiostatic scanning experiments as a function of temperature, what you find is the temperature decreases. You get the growth of a peak that we just call a gamma peak for lack of any other identification. It is something that comes out of the spectrum because the oxygen

overload goes to higher values enabling you to charge this other species, which probably is related to some nickel-poor compound.

That's what gives rise to the extra capacity. The capacity you get at 20 degrees is approximately equal to theoretical capacity of the electrode, for one electron transducer. And then you get an enhancement at lower temperatures by the introduction of this peak. If you do a potentiostatic stand so that we don't go into this subpeak region, then the capacity remains at the theoretical value.

To get the capacity up at lower temperature, you need to do some of the new things that the commercial industry has done over the years to improve charge efficiencies at the higher temperatures; sodium and various additives that increase the oxygen over potential, to enable you to charge that material. So that having a reasonably steep slope there, perhaps 120-percent utilization of the theoretically active material at roughly zero Centigrade is, I think, a reflection of good and properly prepared nickel electrochemically deposit electrode, we shouldn't try to wash it out.

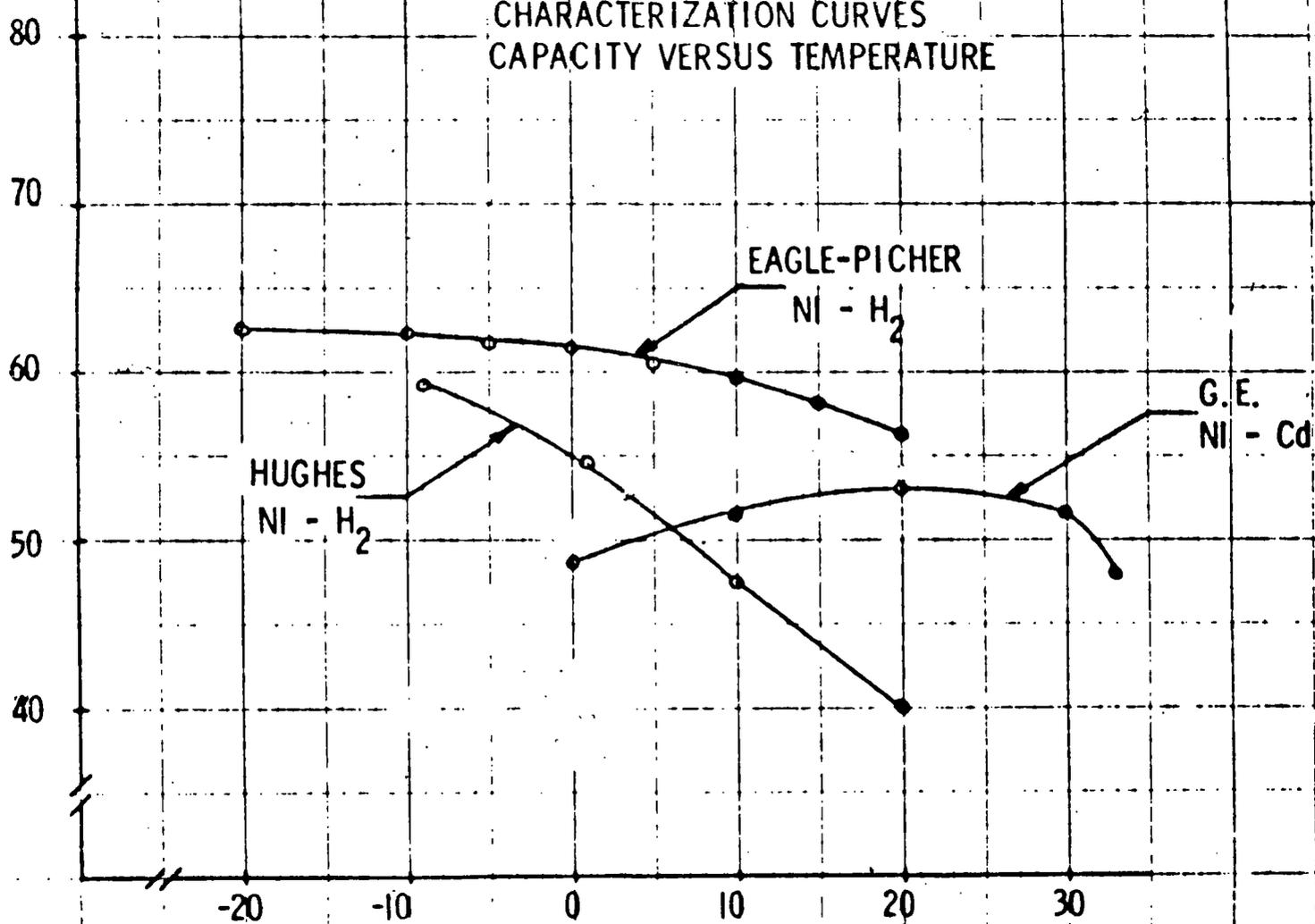
OTZINGER: One thing we did notice at some higher rate charging that we did at these low temperatures, we did have multiple level voltage indicated. There was a real distortion.

MAURER: That's right. One other thing I didn't mention is at 20 degrees we can get the same effect if we simply charge at a high enough rate. You get enhancement somewhere between  $C/5$  and  $C/2$ . You get theoretical capacity below that; 120 percent above that.

CHARACTERIZATION CURVES  
CAPACITY VERSUS TEMPERATURE

CAPACITY (AMPERE-HOURS)

TEMPERATURE (DEGREES CELSIUS)



530

B. OTZING  
7-30-79

Figure 6-44

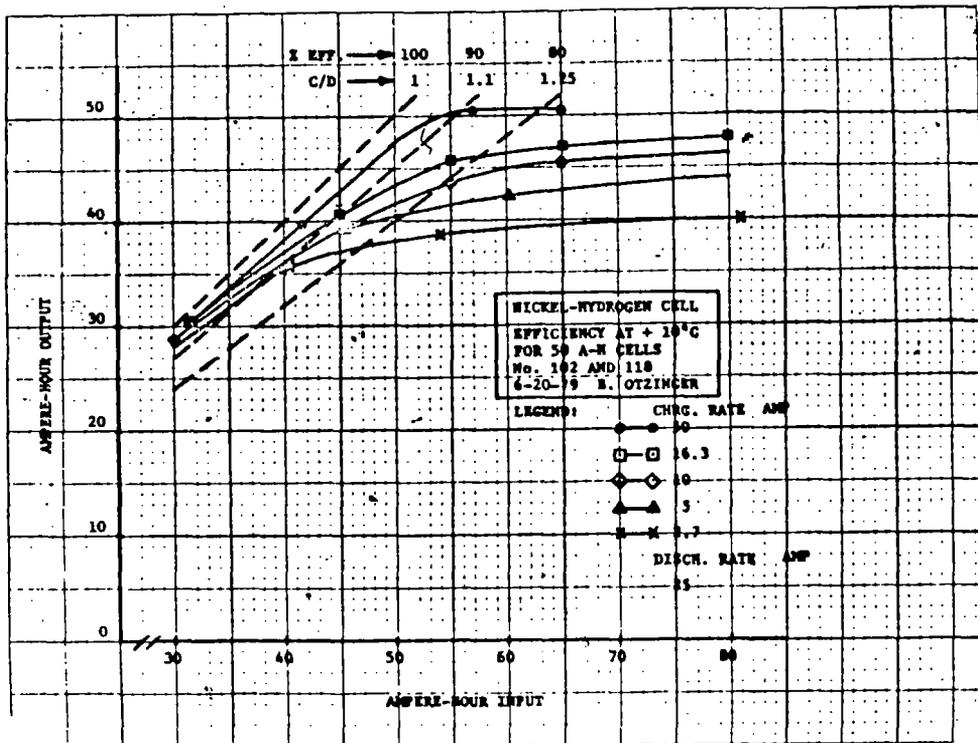


Figure 6-45

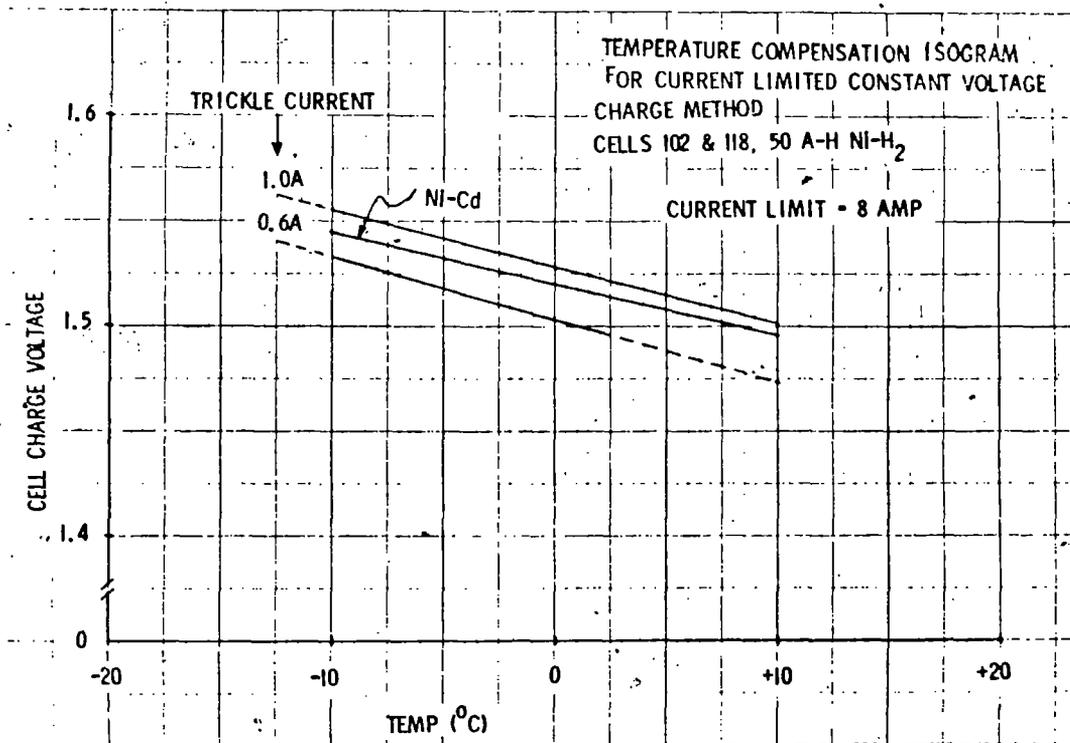


Figure 6-46



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